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Each of the paper's three research objectives was achieved. Since none of the radar detection models satisfactorily addressed radar radiation patterns a model was proposed based on a software package developed at the Naval Research Laboratory. In addition, during the course of the research for this paper a requirement for the effective centralized management of computer supported war games development in the U.S. Navy was perceived.

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RADAR DETECTION MODELS IN
COMPUTER SUPPORTED NAVAL
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A thesis presented to the Faculty of the U.S. Army
Command and General Staff College in partial
fulfillment of the requirements for the
degree

MASTER OF MILITARY ART AND SCIENCE

by

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CHAPTER 1

1.1. Background. War gaming, as applied to the military, is a technique which may be used by a force commander to evaluate the relative merits of various courses of action available to him for the accomplishment of his mission. In tactical situations, war gaming enables the commander to fight a battle before it commences. Through war gaming he weighs each of his tactical strategies against each of the enemy's anticipated responses or initiatives. In addition to being a useful concept for the analysis of an immediate tactical situation, war gaming can be of value in the training of combat commanders.

In training situations, war gaming allows commanders and future commanders to exercise and develop their analytical skills, to examine the validity of established doctrine and to explore the viability of evolving tactical concepts. The classroom tactical training environment often reduces war gaming to a rigidly defined process called a war game. A war game may be technically classified as a game of strategy. As such, a war game is defined by its set of rules. The purpose of these rules is to simulate as accurately as possible, within the constraints of resources, the scene of battle. The rules specify the opposing forces and what actions these forces are allowed, or required to take in response to each others tactical strategies. If a war game involves the use of chance devices, or if

chance occurrences are an integral part of the scenario the game is simulating, then the rules specify how chance events shall be interpreted. Finally, the rules determine when the game ends and its outcome.

Depending on the set of rules selected, war games are applicable to all branches of the Armed Forces. This paper will be concerned with certain aspects of one category of naval tactical war games.

As with war games in general, a naval tactical war game permits the evaluation of various tactical options under the constraints of a specified set of rules. Numerous naval combat scenarios may be usefully analyzed through the use of a war game. The most critical and demanding is the "multi-threat" scenario in which a surface combatant, or group of combatants, must defend against opposing surface, sub-surface, and air forces. Since hostile surface ships, submarines, and aircraft are capable of delivering sophisticated anti-ship capable missiles (ASCM's) against friendly naval forces, the primary tactical threat to be countered in the multi-threat scenario is the airborne threat of the ASCM. Therefore to be useful, naval tactical war games must provide for the realistic simulation of the detection, engagement, and destruction of ASCM's. It should be noted at this point that ideally the ASCM launch platform should be destroyed prior to its launching of an ASCM.

Once a scenario is established and a set of rules defined, a naval tactical war game may be produced as a purely manual game, a purely computer-driven game, or some combination of the two, depending on the level of complexity desired. Computer-driven and computer-assisted war games have an advantage over manual games in that they may, in general, be played more rapidly, and therefore permit the evaluation of more tactical decisions within a given period of time. Because of this advantage only computerized naval tactical war games will be addressed in this paper.

To be of value, a computerized naval tactical war game simulating the engagement between surface combatants and ASCM's must be provided with a realistic detection model for the airborne threat posed by the ASCM. If the detection of an ASCM cannot be satisfactorily modeled, then its engagement and destruction cannot be adequately simulated, since in the sequence of events it is necessary to detect a target before weapon systems can be brought to bear. The presence of an ASCM may be detected by surface combatants in numerous ways. It may be detected visually by the ship's lookouts, under certain conditions it may be detected acoustically by the ship's sonar, it may be detected by the ship's electronic support measures (ESM) receivers, or it may be detected by the ship's surface search and long range air search radars. Although all of these detection methods can be simulated and can, in fact, provide the indication of the presence of an ASCM, except for radar (and, in limited cases, sonar), they provide only a line of bearing to the

ASCM. A line of bearing by itself is not sufficient for the designation of weapon systems to the ASCM. ESM, in addition to a line of bearing, provides excellent qualitative information concerning an ASCM, but depends on active electromagnetic emissions from either the launch platform or the missile itself. Of the various detection systems, only the ship's surface search and long-range air search radars provide the range and bearing information required to permit the engagement of an airborne ASCM by the ship's weapon systems. Therefore, computerized naval tactical war games must use realistic radar models to simulate the detection of airborne ASCM's. Without an adequate radar simulation, the tactics used during the conduct of a computerized naval tactical war game to counter the ASCM threat can not be validly evaluated.

1.2. Purpose. It is the purpose of this paper to first examine the parameters required for a realistic radar detection model. Second, to determine whether or not existing computerized naval tactical war games utilize adequate radar detection models for the purpose of countering airborne threats. And finally, if adequate radar simulations are not currently used, or planned for use, in computerized naval tactical war games, to suggest a model adaptable to computer games.

CHAPTER 2

2.1. Introduction. Radar technology is a complex and continuously expanding field of research. This technology has found numerous applications, from simple devices for measuring the speed of an automobile to immense systems capable of tracking artificial earth satellites and ballistic missiles. Each radar system, regardless of complexity, is designed around a set of operating parameters, which interact with the physical environment to uniquely define that system's specific capabilities. Therefore, the radar detection models used in computerized naval tactical war games must consider the operating param[illegible] f actual radar systems in use on board naval units and must also account for the physical environment in which those radar systems most often function.

Since, as discussed in Chapter 1, this paper is concerned only with those computerized naval tactical war games which deal with the surface combatant versus anti-ship capable missile (ASCM) engagement scenario, the radar systems of interest are ship mounted, long-range air search systems. The remainder of this chapter will be devoted to a discussion of some of the theory and parameters associated with this type of radar system. This discussion will be oriented towards developing an understanding of those radar system and environmental characteristics and conditions which, as a minimum, must be considered in a realistic analytical radar detection model. The discussion of radar theory and modeling contained in

this chapter is merely an introduction, interested readers are encouraged to refer to the references listed in the bibliography for a more thorough examination of radar theory.

2.2. A pulse modulated air search radar is an active system which emits precisely spaced pulses of electromagnetic energy. These pulses of energy illuminate, and are partially reflected from, an airborne target. A portion of the reflected energy is received by the radar set and the range to the target is determined by the time differential between the transmission of a pulse and the receipt at the radar receiver of the pulse's reflected energy. The range to the target, from the radar, is determined by the following relation:

$$R = \frac{ct}{2} \tag{2.1}$$

where: R = Range to the target

c = the average speed of electromagnetic propagation, 164,000 NM/sec

t = the time difference between the transmission of a radar pulse and the receipt of the pulse's reflected energy at the radar receiver

The pulse modulated radar functions basically is two modes: transmit and receive. In the transmit mode the radar set emits a pulse of electromagnetic or radio frequency (RF) energy, the duration of which is measured microseconds. When a pulse of required duration has been formed the radar set's transmitter shuts down and

the radar's receiver is switched into operation. The radar set remains in the receive mode for a period of time sufficient to allow the previously transmitted pulse to illuminate a target and return to the radar set. This period of time that the radar receiver is functioning determines the radar's theoretical maximum unambiguous detection range. At the expiration of the predetermined reception period the receiver is switched off and the transmitter emits another pulse. This sequence of pulse transmission and receiver operation continues as long as the radar is operated.

2.3. Radar Components. Figure 2.1 illustrates the major components of a pulse modulated radar and their relationship to one another.

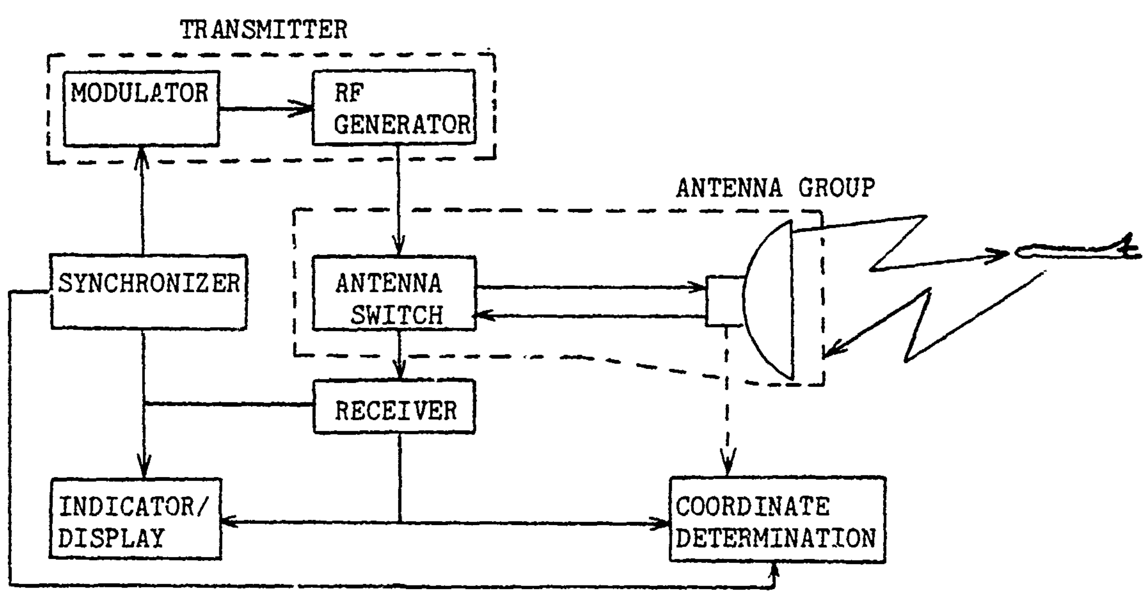

Figure 2.1. Pulse Radar System Block Diagram[1]

As depicted in figure 2.1, a pulse modulated radar set can be divided into five major equipment groupings: synchronizer, transmitter, receiver, indicator/display and coordinate determination, and antenna. Additionally, a well regulated source of power is required by each component.[2]

2.31. Synchronizer. The synchronizer is the heart of a pulse modulated radar set. It provides a synchronization signal which coordinates the alternate functioning of the radar's transmitter and receiver. These synchronization signals determine the rate at which RF energy pulses will be transmitted--the Pulse Repetition Rate (PRR)--and the length of time the radar will be in the receive mode during each transmit/receive cycle.[3] Further, these synchronization signals provide the precise time reference required by the indicator/display and coordinate determination group to accurately provide target range and bearing information to the radar set operator.

2.32. Transmitter.

2.32.1. Modulator. The modulator section of the transmitter group, using signals from the synchronizer, controls the operation of the transmitter's active components. This control function results in a series of pulses of a specified duration, form, and amplitude used to drive the transmitter RF generator module.

2.32.2. RF Generator. The RF generator produces high frequency oscillations. These oscillations define the characteristic operating frequency of the radar set. The initiation and cessation of the RF oscillations is determined by the duration of the pulses provided by the modulator. Additionally, the initial amplitude of the generated RF signal is directly related to the form of the modulator pulses. The interaction of the modulator pulses and RF generator produces RF energy packets of specified form and duration which are amplified and transmitted by the radar set. Figure 2.2 illustrates the formation of RF energy pulse packages by the radar transmitter and synchronizer groups.

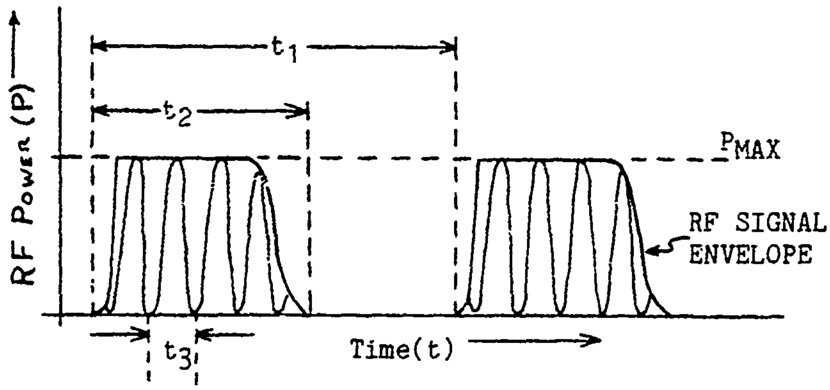

Figure 2.2. RF Energy Pulse Packets. t_1 = 1/PRR, determined by synchronizer, one transmit/receive cycle; t_2 = Pulse Width (PW), determined by the modulator; t_3 = 1/f, f is the characteristic frequency of the radar set, determined by the RF generator; P_{MAX} = Maximum Transmitted power, determined by the modulator and RF power amplifier; RF Signal Envelope, determined by the form of the modulator pulse.

2.33. Receiver. The radar receiver receives and amplifies RF energy reflected from targets. The operation of the receiver is controlled by synchronization signals from the synchronizer.

2.34. Indicator/Display and Coordinate Determination. This grouping takes target signal information from the receiver and, with the time reference provided by the synchronizer, processes that information into an intelligible display for the radar operator. Air search radar indicator/display units are available in numerous forms, however, in general they display, in one manner or another, target range and bearing information, which has been processed for display by the radar's coordinate determination elements. In some cases a third dimension, target altitude, is also provided to the system operator.

2.35. Antenna. The antenna equipment grouping includes the radiating element, RF energy transmission lines from the radar transmitter and to the receiver, antenna direction control devices (usually rotating), and the antenna transmit-receive (T-R) switch. Since pulse radars usually use the same antenna for both transmission and reception, a device is necessary to protect the radar's sensitive receiver from the powerful bursts of RF energy emitted by the transmitter. It is also necessary to insure that the reception of the reflected signal is not degraded by feeding the weak returning signal into both the receiver and the transmitter, since that portion of the signal entering the transmitter would be lost. The

device which performs both of these functions is the antenna transmit-receive (T-R) switch. During the transmit mode the T-R switch removes the radar receiver from the antenna transmission line system, isolating it from the transmitter. Conversely, in the receive mode the T-R switch removes the radar transmitter from the antenna transmission line system and directs all of the returning signal to the radar receiver for processing.

2.4. The interaction of a radar set's components results in a set of operating parameters, or characteristics, the values of which determines the radar's capabilities and unique signature. For the purpose of developing a war game radar detection model, the major parameters of interest are: wave length (λ), radiated power, pulse repetition rate (PRR), pulse width, receiver sensitivity, antenna gain, beam width, and scan rate.

2.41. <u>Wave Length (λ)</u>. Wave length is probably the fundamental radar parameter. It is related to the radar's operating frequency, f, as follows:

$$f = c/\lambda \qquad (2.2)$$

where: c = the average speed of electromagnetic propagation

From this equation it can be seen that the wave length and operating frequency are inversely related. Therefore, as the radar's operating frequency is increased, or decreased, its wave length is

decreased, or increased respectively. Without going into specific details, the wave length of a radar set influences radiated power, receiver sensitivity, antenna gain, and the effective reflecting area of a target, all of which affect the dection range of the radar.[4] Additionally, wave length determines, in part, the rate at which the radar signal is attenuated and refracted by atmospheric conditions. The capability of the radar to resolve targets of a particular size is dependent on its operating wave length. And finally, wave length determines the size and construction of radar set components, particularly antennas and transmission lines.

2.42. Radiated Power. The radar's maximum effective detection range is directly related to its radiated power. Normally radar radiated power, P_{RAD}, is characterized by the transmitter pulse power, P_{PULSE}. The relation between P_{RAD} and P_{PULSE} is

$$P_{RAD} = \eta P_{PULSE} \qquad (2.3)$$

where: η = the efficiency of the transmitter to antenna transmission line

Transmitter pulse power is defined as the average power emitted by the transmitter during the duration of a pulse.[5] This should not be confused with average transmitter power, which is defined as the power emitted by the radar transmitter averaged over one complete

radar transmit and receive cycle. Average transmitter power, P_{AV}, and transmitter pulse power, P_{PULSE}, are related as follows:

$$P_{AV} = (PW)\,(PRR)\,(P_{PULSE}) \qquad (2.4)^{6}$$

where: PW = the Pulse Width, or duration, measured in seconds

PRR = Pulse Repetition Rate, measured in cycles per second, or Hz

From (2.4), $P_{RAD,\ AV} = \eta P_{AV}$

where $P_{RAD,\ AV}$ = the average radiated power

As already discussed, radar detection range, R, is directly related to radiated power, P_{RAD}. Therefore, if radiated energy is

$$W_{RAD} = (P_{RAD})\,(PW) \qquad (2.5)$$

$$= (\eta P_{PULSE})\,(PW)$$

and $R \sim (W_{RAD})^{1/4}$, an increase in radar detection range can be obtained by either increasing the transmitter pulse power while holding pulse duration constant, or by increasing the duration of the pulse while holding the transmitter pulse power constant.[7]

2.43. <u>Pulse Repetition Rate (PRR)</u>. The PRR is defined as the number of pulses per second emitted by a radar transmitter. This equates to the number of transmit/receive sequences which the radar set cycles through each second. The PRR determines the maximum unambiguous radar detection range.

$$R_{MAX,\ UNAMBIGUOUS} = c/(2\ PRR) \qquad (2.6)$$

Additionally, for a given scan rate[8] and antenna beam width, the PRR determines the number of pulses which illuminate a target during one sweep of the radar beam. This in turn directly affects the probability of target detection, since the greater the number of pulses impinging on a target the greater will be the aggregate reflected signal received by the radar set.

These two results of PRR present a dilemma. To increase the probability of target detection, the PRR should be increased. However, if PRR is increased, then $R_{MAX,\ UNAMBIGUOUS}$ is decreased and vice versa. This dilemma can be partially solved through the use of special electronic circuitry to eliminate target ambiguity, permitting PRR's to be increased by as much as a factor of five while not decreasing $R_{MAX,\ UNAMBIGUOUS}$.[9] However, in general the relation expressed in equation (2.6) is valid.

2.44. <u>Pulse Width (PW)</u>. Radar pulse width is defined as the duration, usually measured in microseconds, of the transmitted pulse (see figure 2.2). Pulse width determines, in part, both minimum radar detection range and radar range resolution. Further, PW determines the amount of RF energy emitted by a radar over a given period of time (see equation 2.5), which in turn determines the amount of energy illuminating a target. Therefore, increasing PW increases the RF illumination of a target, thereby increasing the amount of reflected signal, resulting in increased range for a given probability of detection. However, PW can not be increased without

consideration of other factors. Increasing PW, while improving long range detection, increases minimum detection range and degrades range resolution.

2.45. <u>Receiver Sensitivity ($P_{REC, MIN}$)</u>. All other parameters remaining constant, the maximum detection range, R_{MAX}, of a radar set is determined by the minimum reflected signal strength that the radar receiver is capable of receiving, amplifying, and processing for display. This minimum signal power level, $P_{REC, MIN}$, is defined as receiver sensitivity. The normal convention is to describe an increase in receiver sensitivity as a decrease in $P_{REC, MIN}$. Therefore, since $R \sim 1/(P_{REC, MIN})^{1/4}$, the more sensitive the receiver, (the lower $R_{REC, MIN}$) the greater the radar range.[10] It is often more desirable, and technically feasible, to increase the range of a radar set by increasing its sensitivity, rather than increasing the set's radiated power. In particular, an increase in radiated power requires increased station size, increased weight, and increased cooling capacity, all of which are undesirable.

2.46. <u>Antenna Gain (G)</u>. Antenna gain, also referred to as the antenna amplification factor, is a function of the radar's operating wave length (λ) and the size and geometry of the radar antenna. It describes the concentration of radiated RF energy resulting from the use of a directional antenna.[11]

$$G = \frac{4\pi S_A}{\lambda^2} \qquad (2.7)^{12}$$

where: S_A = the effective capture area of the radar antenna

By concentrating the radiated power into a narrow beam, the effective power of the radar set is increased and therefore its maximum detection range is also increased. Additionally, since the same antenna is generally used for both transmission and reception, G also affects the ability of the radar to receive reflected signals. As G increases, the more efficient will be the reception of reflected signals by the radar's receiver.

2.47. Beam Width. Associated with antenna gain is antenna beam width. The greater the value of G the narrower the beam width. Because of antenna construction, the beam of an air search radar is usually very narrow in the horizontal plane, but wide in the vertical plane. This permits the tracking of air targets at various altitudes without the necessity of adjusting the antenna in elevation, while at the same time permitting the accurate determination of target azimuth. The accuracy of azimuth determination is directly related to antenna beam width in the horizontal plane. As beam width is narrowed, the accuracy of target azimuth information is increased. However, for a given PRR and scan rate, narrowing the horizontal beam width reduces target illumination opportunity. That is, reducing the beam width reduces the period of time that a target remains within the illuminating beam. This in turn reduces the probability of target detection.

2.48. <u>Scan Rate</u>. Scan rate is the number of times the radar sweeps its assigned search sector per unit time. The reciprocal of scan rate is scan period, the interval of time required to illuminate each point in the radar search sector. Long range air search radars generally utilize a circular scan. Scan rate, therefore, is measured in revolutions per minute and scan period is found from the expression

$$T_{SCAN} = 60/N_a \qquad (2.8)^{13}$$

where: N_a = Antenna RPM

For a given horizontal beam width, increasing T_{SCAN} (decreasing scan rate) increases target illumination opportunity. That is, the greater the value of T_{SCAN}, the more pulses will impinge on, and be reflected from, the target. Therefore, if N_p is the minimum number of reflected pulses required to be integrated by the radar receiver in order to detect a target with a specified probability, then the desired antenna scan period for circular scanning air search radars will be

$$T_{SCAN} \geq N_p \, 360/(PRR)\,(BW) \qquad (2.9)^{14}$$

where: BW = the horizontal beam width in degrees

2.5. Once the various radar parameters discussed in the preceding section have been determined, or specified, the detection capability of the simulated radar set can be established.

2.51. Minimum Detection Range. The minimum detection range of a radar set is a function of pulse width (PW), receiver recovery time (T_R), and the range resolution (R_R) of the indicator/display equipment in use. Receiver recovery time is the period of time required for the radar transmit-receive switch to remove the transmitter from the system and place the receiver into operation. Indicator/display equipment range resolution is simply a numeric value expressing, in a unit of length, the accuracy of target range data presented on the radar set indicator/display equipment. The relationship between these parameters which define minimum radar range is

$$R_{MIN} = \frac{c\ (PW + T_R)}{2} + R_R \qquad (2.10)$$

2.52. Maximum Detection Range. The determinations of maximum radar detection range is an involved subject requiring rigorous physical and statistical analysis of radar propagation phenomena. Readers with a background in mathematics and a desire to delve further into the subject will find excellent references listed in the bibliography. For the purpose of determining maximum radar detection range in radar simulations used in computerized naval tactical war games, useful results can be obtained from several relatively simple mathematical relationships.

2.52.1. Maximum Unambiguous Detection Range ($R_{MAX,\ UNAMBIGUOUS}$). Since during one complete transmit-receive cycle a radar pulse must travel from the radar to the target and return, the maximum unambiguous detection range is determined by the radar sets PRR, as previously discussed in Section 2.43. Equation 2.6 may be used to determine $R_{MAX,\ UNAMBIGUOUS}$.

In general a radar PRR is selected in order to provide a value of $R_{MAX,\ UNAMBIGUOUS}$ great enough so that the strength of a signal reflected from a target beyond that range would be below $P_{REC,\ MIN}$. If by chance a signal returning from a target beyond $R_{MAX,\ UNAMBIGUOUS}$ exceeds $P_{REC,\ MIN}$, then that target would be displayed at a range equal to the difference between its actual range and $R_{MAX,\ UNAMBIGUOUS}$, that is

$$R_{DISPLAYED} = R_{ACTUAL} - R_{MAX,\ UNAMBIGUOUS}$$

For example, if $R_{MAX,\ UNAMBIGUOUS}$ equals 270 NM and R_{ACTUAL} equals 290 NM, then the target would appear on the radar indicator/display at 20 NM.

2.52.2 Maximum Detection Range (R_{MAX}). Maximum unambiguous detection range, although a useful starting point in determining whether or not an airborne target will be detected at a given range, does not consider numerous important parameters. An expression which does is

$$R_{MAX} = \left[\frac{P_{RAD}\ G S_A\ \sigma_T}{16\pi^2\ P_{REC,\ MIN}}\right]^{1/4} \qquad (2.11)$$

where: P_{RAD} = Radiated Power
G = Antenna Gain
σ_T = Effective Target Radar Cross Section
S_A = Effective Antenna Area
$P_{REC,\ MIN}$ = Receiver Sensitivity

Since $G = 4\pi S_A/\lambda^2$ equation 2.11 can be rewritten as:

$$R_{MAX} = \left[\frac{P_{RAD}\ S_A^2\ \sigma_T}{4\pi\ \lambda^2\ P_{REC,\ MIN}}\right]^{1/4} \qquad (2.12)$$

where: λ = operating wave length

If a value known as the classification factor, V_c, can be determined, then equation 2.12 becomes:

$$R_{MAX} = \left[\frac{P_{RAD}\ S_A^2\ \sigma_T}{4\pi\ \lambda^2\ P_{REC,\ MIN}\ V_c}\right]^{1/4} \qquad (2.13)$$

V_c is a factor which considers signal-to-noise ratio and the integration of pulses to obtain a desired probability of detection.[15]

2.6. Radar Horizon. Although the distance between an airborne target and the radar set may be less than either R_{MAX} or $R_{MAX,\ UNAMBIGUOUS}$ the target, depending on its altitude, may be below the radar horizon. Electromagnetic radiation emitted from a radar follows essentially line of sight paths. The radiation path tangent to the earth surface defines the radar horizon and lower limit of the radar detection envelope. In principle only targets above the radar horizon, as depicted in figure 2.3, can be illuminated, and therefore detected by a radar.

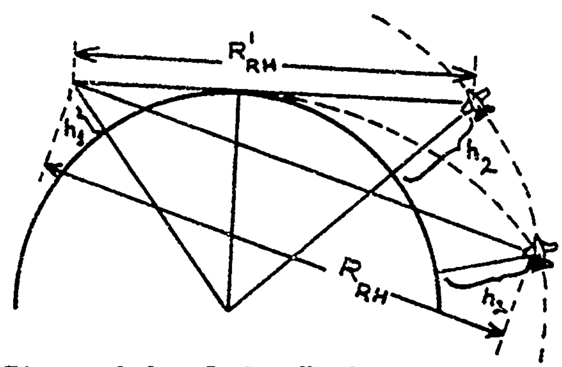

Figure 2.3. Radar Horizon
A is the location of radar; B is the location of target, assuming no refraction; C is the location of visible target assuming normal refraction

Given antenna height h, and target altitude h_1 the maximum line of sight range at which the target can be illuminated is

$$R'_{RH} = \sqrt{2R_e} \ (\sqrt{h_1} + \sqrt{h_2}) \qquad (2.14)$$

where: R_e is the radius of the earth and h_1 and $h_2 \ll R_e$

Equation 2.14 does not take into account any refraction of electromagnetic radiation which may occur because of atmospheric conditions. In fact, electromagnetic radiation, even at the frequency of most search radars, is refracted by the earth's atmosphere. If the degree of refraction can be determined, then equation

2.14 can be revised to reflect actual environmental conditions by adjusting the coefficient of the term $(\sqrt{h_1} + \sqrt{h_2})$. Under standardized atmospheric conditions electromagnetic radiation, in the frequency range of most long range air search radars, is refracted sufficiently so that targets at altitude h_2 out to range R_{RH} in figure 2.3 are illuminated. The radar horizon under normal refraction is determined as if the earth's radius was one third greater than it actually is. That is, under normal refractive conditions the earth's effective radius, R_e effective, equals 4/3 R_e, therefore:

$$R_{RH} = \sqrt{2\ (4/3\ R_e)}\ (\sqrt{h_1} + \sqrt{h_2})$$

therefore given R_e = 3444 NM and h, and H_2 in feet,

$$R_{RH} = 1.25\ (\sqrt{h_1} + \sqrt{h_2}) \qquad (2.15)^{16}$$

2.7. <u>Radar Interference Patterns and Fade Zones</u>. In addition to the atmosphere, the earth's surface influences the propagation of radar signals, a fact that a radar detection model must address. The transmission and reception of electromagnetic radiation by the antenna of a radar set occurs within specified solid angles in both

the vertical and horizontal planes. These angles are the antenna's vertical and horizontal beam widths respectively. In ship mounted air search radars the horizontal beam width is usually quite small, on the order of one to three degrees, while the vertical beam width is very large, approaching ninety degrees. Because of the antenna's very wide vertical beam width, electromagnetic radiation from the radar follows at least two primary paths from the antenna to the target and back again. The first is the direct path and the second is the reflected path, from the antenna to the earth's surface to the target and back.

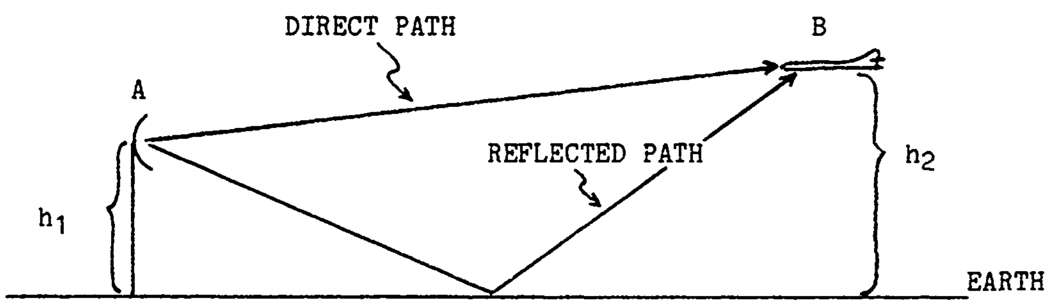

Figure 2.4. Interference of Electromagnetic Radiation from Direct and Reflected Path Propagation

The strength of the electrical field at B in figure 2.4 is the vector sum of the direct and reflected radiation paths.[17] To establish the strength of the radar signal at point B it is necessary to know the phase relationship between the direct and reflected path signals. If the two signals are in phase, zero degrees difference, at point B, then constructive interference occurs and the total signal strength may be as much as twice the direct path signal

strength. If on the other hand, the two signals arrive 180 degrees out of phase, then destructive interference occurs at B and the total signal strength will be some value less than the direct path signal strength, possibly zero. If the phase relationship between the direct and reflected path signal is some value between these two extremes, then the strength of the radar signal at point B will lie somewhere between zero and twice the direct path signal strength.

The constructive and destructive interference of the direct and reflected path radar signals result in a pattern of signal lobes in the vertical plane (see figure 2.5). The number of such lobes is determined by the radar antenna's directivity in the vertical plane, its height above the surface of the earth, and the radar set's operating wave length, λ. In the case of a radar antenna which is non-directional in the vertical plane, the number of lobes is

$$N = h_1 / (\lambda/2) \qquad (2.16)$$ [18]

where: h_1 = height of the radar antenna above the earth

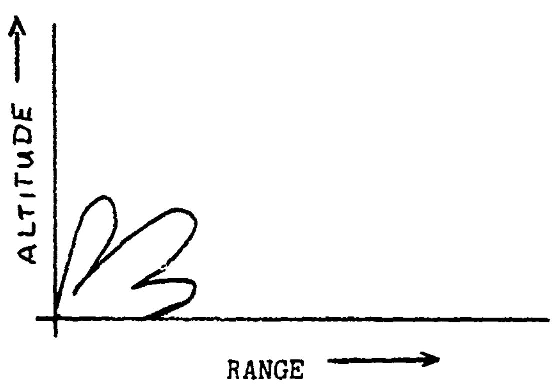

Figure 2.5. Radar Signal Lobes in the Vertical Plane

Since most shipboard long-range air search radars use a circular scan in the search mode, these lobes are swept through 360 degrees resulting in a pattern, in the horizontal plane, of alternating annular rings, or zones, of signal strength maxima and minima. The specific horizontal pattern is a horizontal section at a given altitude of the lobe pattern in the vertical plane (see figure 2.6).

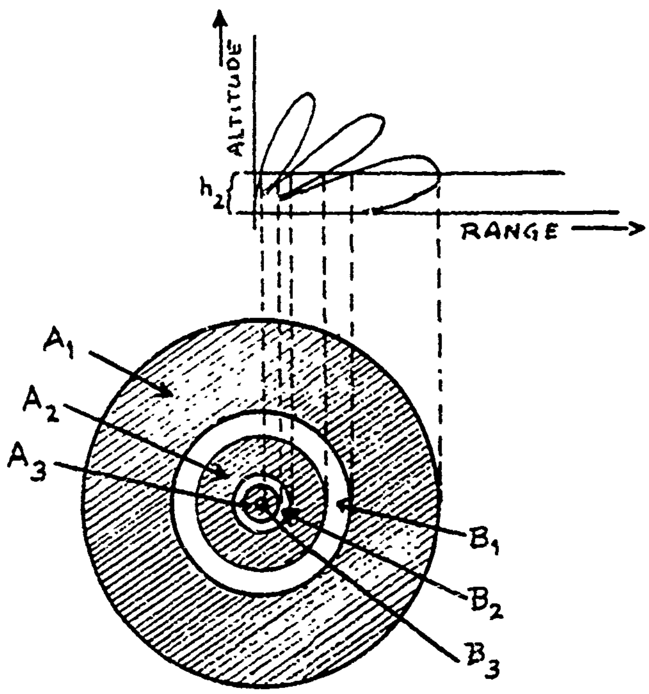

Figure 2.6 Example of Horizontal Interference Pattern Resulting from Vertical Lobing of the Radar Radiation Pattern

In figure 2.6, zones A_1, A_2, and A_3 represent areas where the total strength of the radar signal is equal to, or greater than, the direct path signal strength. Zones B_1, B_2, and B_3 are those areas where the total radar signal strength is less than the direct path signal strength. Therefore, as an airborne target

approaches the ship mounted air search radar set at a constant altitude (for example h_2 in figure 2.6) it passes through zones of varying radar signal strength. As the target illuminating strength varies, the strength of the signal reflected from the target varies in direct proportion to the incident signal. During some range intervals, as the target approches the radar, the strength of the signal reflected from the target will fall below $P_{REC,\ MIN}$, resulting in an interruption of target observation.[19] When this occurs the target is said to have entered a "fade zone".

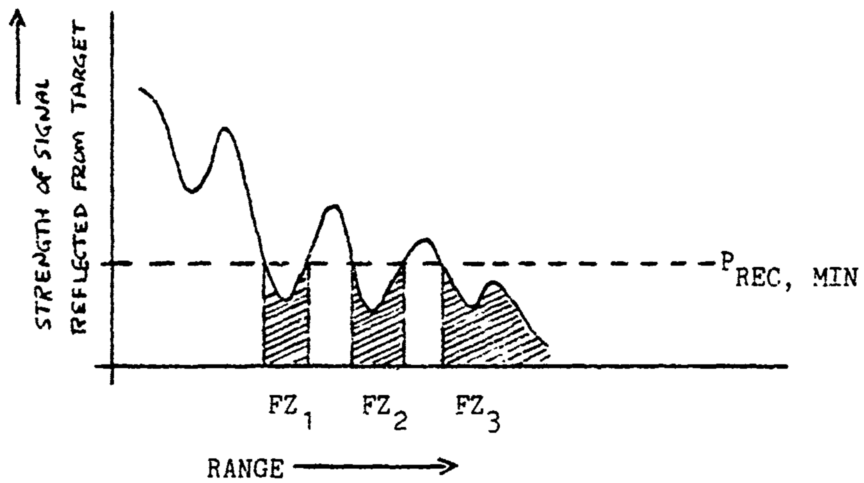

Figure 2.7. Example of the Change in the Reflected Power of a Signal Reflected from a Target Flying at a Constant Altitude. FZ_1, FZ_2, and FZ_3 are "Fade Zones" where the Target is not observed.[20]

In developing a realistic radar detection model for a computerized naval tactical war game, it is necessary to ensure that provisions are made to describe the interference pattern and resulting fade zones which exist due to the multiple paths that electromagnetic radiation can follow from the radar to the target and

back. Serious discrepancies in the simulation of radar detection events will occur if a radar model assumes a homogeneous radiation pattern from R_{MAX} to R_{MIN}. Interference pattern, or fade zone, information can be obtained for a radar model either analytically or empirically.

The analytical approach requires a knowledge of the radar radiation pattern in the vertical plane and its polarization. For example, if a radar has a horizontally polarized radiation field then the interference pattern can be related to variations in radar detection range.

$$R_{MAX} = \left(R_{FS,\ MAX}\right)^2 fa\ (\beta)\ \sin\left(\frac{2\pi}{\lambda} h_1 \sin\beta\right) \qquad (2.17)$$ [21]

where: h_1 = height of radar antenna

$R_{FS,\ MAX}$ = Radar maximum free space range, see equation (2.13)

β = Elevation Angle

$fa\ (\beta)$ = a mathematical function describing the antenna radiation pattern in the veritcal plan

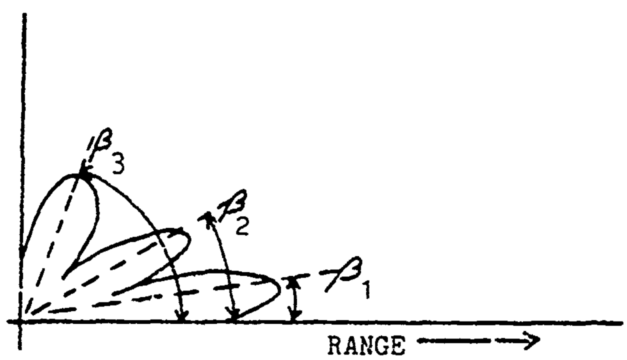

Figure 2.8. Example of Vertical Lobe Pattern Plotted in Polar Coordinates from equation 2.17. β_1, β_2, and β_3 are various elevation angles.

If the radar radiation is vertically polarized, or the target is flying at a low altitude, then mathematical relations other than equation 2.17 must be used to describe the interference pattern in question. These are discussed in detail in Fundamentals of Radar by A.G. Saybel and Theoretical Fundamentals of Radar by V. Ye. Dulevich, A.A. Korostelev et al. (see bibilography) and will not be further elaborated on in this paper.

A simplistic, but possibly useful analytical description of a radar set's interference pattern can be obtained from:

$$N = \frac{4\, h_2\, h_1}{\lambda\, R} \qquad (2.18)$$[22]

where: h_1 = radar antenna height
h_2 = target altitude
λ = radar set operating wave length
R = the range of the target from the radar

When N = 0, 2, 4, 6, . . . the target is in the center of a zone of radar signal minimum, and when N = 1, 3, 5, 7, . . . it is in the center of a zone of radar signal maximum. This relation, equation 2.18, assumes that R is much larger than either h_1 or h_2.[23]

If no additional information is available, analytical methods can be used exclusively in a radar detection model to determine radar fade zone patterns. However, actual fade zone data is often available for particular radars and may be used in radar detection models. This data is generated by flying target aircraft at specified altitudes towards and away from the radar in question.

Regardless of the approach used, analytic or emperical, a radar detection model must account for a search radar's vertical lobing and horizontal interference pattern.

2.8. Radar Operator. A final factor that should be considered in a valid radar detection model is the radar operator. Although a radar set is capable of receiving and processing a target reflected signal of a certain strength, the operator must recognize the presence of the target signal on the indicator/display unit and react accordingly. The various human factors which interact to determine whether or not the operator will recognize the target signal are difficult to quantify in a deterministic manner. However, for the purposes of a radar detection model the function of the radar operator can easily be simulated by a Monte Carlo process.

2.9. Conclusion. This chapter has discussed briefly some of the theory and parameters associated with shipboard, long-range, air search, pulse modulated radar systems. This discussion has not been intended to be all inclusive, but merely introductory. In particular, the statistical and probabilistic aspects of radar operation and detection theory has only been mentioned in passing, and are themselves the subjects of numerous scientific publications. The primary purpose of this chapter has been to alert the reader to the complex nature of radar detection and to identify a minimum listing of radar parameters and characteristics which must be considered in

a valid radar detection model for computerized naval tactical war games. This compilation of parameters and characteristics will form the basis of the critical analysis of radar detection models currently used in computerized naval tactical war games.

NOTES

1. K. M. Listov and K. N. Trofimov, Radio and Radar Technology and Its Application., trans. Foreign Technology Division, Air Force Systems Command, Wright-Patterson AFB, Ohio (Moscow: Voyennoye Izdatel'stvo Ministerstva Oborony Soyuza SSR, 1960), p. 259.

2. Ibid., p. 260.

3. The Pulse Repetition Rate is also known as the Pulse Repetition Frequency (PRF).

4. Listov and Trofimov, Radio and Radar Technology and its Application, p. 300.

5. V. Ya. Tsylov, et al., Handbook of Radar Engineering Fundamentals, trans. Translation Consultants, Ltd (Moscow: Military Publishing House of the Ministry of Defense of the USSR, 1967), p. 80.

6. Ibid.

7. Ibid.

8. Scan Rate, the rate at which the radar set's beam scans a given point in space. For most long range air search radars utilizing rotating antennas, scan rate is expressed in revolutions per minute.

9. V. Ya. Tsylov et al., Handbook of Radar Engineering Fundamentals, p. 82.

10. Ibid, p. 81.

11. Listov and Trofimov, Radio and Radar Technology and its Application, p. 299.

12. V. Ya. Tsylov et al., Handbook of Radar Engineering Fundamentals, p. 81.

13. Ibid., p. 67.

14. Ibid., p. 66.

15. For a complete discussion see chapter 1 of V. Ya. Tsylov et al., Handbook of Radar Engineering Fundamentals.

16. In equation 2.15 the factors and dimensions required to convert feet to nautical miles are contained in the constant 1.25.

17. V. Ye. Dulevich et al., Theoretical Fundamentals of Radar, trans. Air Force contract AF 33(657)-16408 (Moscow: Izdatel'stvo "Sovetskoye Radio", 1964), p. 196.

18. A. G. Saybel', Fundamentals of Radar, trans. Foreign Technology Division, Air Force Systems Command, Wright-patterson AFB, Ohio (Moscow: Izdatel'stvo "Sovetskoye Radio", 1961), p. 276.

19. V. Ye Dulevich, A.A. Korostelev, et al., Theoretical Fundamentals of radar, p. 207.

20. Ibid., p. 208.

21. A. G. Saybel', Fundamentals of Radar, p. 276.

22. The ARRL Antenna Book, 13th ed. (Newington, Connecticut: American Radio Relay League, 1974), p. 318.

23. Ibid.

CHAPTER 3

3.1. Introduction. Chapter 2 briefly discussed some of the theory and parameters associated with shipboard, long range, air search radars which, as a minimum should be included in radar detection models for computerized naval tactical war games. Using that theory, and those parameters, as a base line, five computerized naval war games, with tactical applications, were evaluated. The games examined included both operational and planned computerized naval war games. Three of the five were evaluated using available documentation. The remaining two games, although currently in use, have not yet been fully documented, therefore their evaluation was accomplished primarily through telephone interviews with their designers and programmers.

The five games examined were the Sea Warfare Integrated Model (SWIM), Warfare Analysis and Research System (WARS) Phase 2A, Naval Tactical Action Game (NAVTAG), Interactive Carrier-Exclusive Tactical Analysis Game (ICETAG), and CINCPACFLT Warfare Environment Simulator (CPF WES). The remainder of this chapter will address each of these games individually.

3.2 Sea Warfare Integrated Model (SWIM). SWIM was prepared in 1969 by personnel of the John Hopkins University Applied Physics Laboratory, Silver Springs, Maryland for the Planning Analysis Group (PAG), Assistant for War Gaming MAtters (OP-06C) in the Office of the Chief of Naval Operations. It is a stochastic model of a naval task force versus submarine scenario, programmed for the IBM 7090

and 7094 computers.[1] Although SWIM is primarily an anti-submarine warfare game, it does allow both for the arming of the submarines with anti-ship capable cruise missiles and for the detection of these missiles by surface ship radar.

3.2.1. SWIM Radar Detection Model. The SWIM radar detection model is quite simple. Detections are determined by comparing the distance from the radar platform to the target with the radar horizon, RH, and a randomized detection range, RDET. RH is calculated by the equation:

$$RH = 1.25 \left(\sqrt{ALT\ (D)} + \sqrt{ALT\ (T)} \right) \qquad (3.1)^{2}$$

where: ALT (D) = altitude of the radar platform in feet
ALT (T) = altitude of the target in feet

Equation 3.1 is identical to 2.15 in chapter 2. RDET is the randomized, time dependent, non-horizon limited detection range. It is determined by taking the median detection range for a specific combination of radar platform and target and adding a time dependent, normally distributed random variable, RWC, with mean 0 and variance 1. RWC is used to account for random variations in equipment and environment which affect radar detection ranges and is determined by a combination of two continuous random walk variables.[3] Therefore, as defined by the SWIM radar detection model

$$RDET = \bar{R} + (RWC)\ \frac{\bar{R}}{2} \qquad (3.2)^4$$

where: $\bar{R}$ = the median detection range, that is the range at radar detection occurs fifty percent of the time for a given combination of radar platform and target

RWC = the time dependent value of the combined random walks from the normal distribution

Radar detection of a target occurs with the SWIM simulation when the caluclated distance, R, between the radar platform and the target satisfies the following relationships:

$$R \leq RDET \leq RD \quad \text{or}$$

$$R \leq RH \leq RDET$$

Radar detection will not occur if:

$$RH < R \leq RDET \quad \text{or}$$

$$RDET < R \leq RD$$

3.2.2. Comment. Stochastic modeling is an excellent method for simulating radar detections in a computerized war game. This approach acknowledges the uncertainty of radar detection in any given situation and attempts to quantify this uncertainty through the application of the laws of probability theory. However, the stochastic process used in the SWIM detection model assumes that the variation in radar detection ranges is due equally to unspecified environmental and equipment conditions.[5] Whether or not this is a valid assumption is difficult to say, but it is unlikely that environment and equipment variations would in all cases have an equal

affect on radar detection ranges. Since the environmental and equipment characteristics included in the stochastically determined term RDET are not identified, the validity of the stochastic process used in the SWIM radar model is questionable.

The basic quantity around which the SWIM radar detection model is built is $\bar{R}$, the median range for a specific combination of radar platform and target. The median detection range is defined as that range at which a particular type of radar platform will detect a particular class of target fifty percent of the time. Instead of determining $\bar{R}$ from specific radar, target, and environmental parameters, the SWIM model requires that the user inputs a predetermined table of mediam detection ranges for various combinations of radar platforms, or "detectors", and targets. The set of permissible detectors consists of four subsets of radar platforms: medium surface ship, heavy surface ship, light aircraft (anti-submarine warfare), and heavy aircraft (maritime patrol or search). The available target set is composed of seven subsets of targets: heavy surface ship, medium surface ship, light surface ship, aircraft, helicopter, submarine snorkel, and submarine periscope.[6] These two sets, when combined, result in twenty-eight detector/target combinations, the median detection ranges for which must be determined and provided by the user.

This is a totally unsatisfactory method of addressing median detection ranges since it assumes that the radar detection capability of all platforms within a given subset is equal, and that there is a constant relationship between the subsets of platforms

and their relative ability to detect targets of a designated class. These implied assumptions are not true. First, there is a great deal of variation in the capability of radar platforms of one subset to detect targets of a given class. For example, in the case of "medium surface ships", some may have only one air search radar while others may have two. The types of radars installed may be different, or they may be of the same type, but different models, each with different field changes, all of which will affect their median detection ranges. Secondly, there is no consistancy between the subsets of radar platforms and their relative ability to detect specific classes of targets. A newer "medium surface ship", with the latest state-of-the-art search radar installed, may have a significant radar detection range advantage over an older "heavy surface ship" and vice versa. In order to meanfully utilize median radar detection ranges, it is necessary to calculate the specific median detection range of a specific radar set, installed on a specified platform, using the radar parameters unique to that installation.

In addition to inadequately handling median detection ranges, the SWIM radar model did not consider major environmental effects on radar detection ranges. With the single exception of standard atmospheric refraction, which is accounted for in the radar horizon equation 3.1, the SWIM radar model did not address any significant non-free space radar propagation factors. In particular, it neglected the problem of radiation interference patterns and radar fade zones resulting from the reflection of radar energy from the surface of the earth.

Finally, in addition to the deficiencies discussed above, the SWIM radar model does not provide for the influence of the radar set operator on the detection ranges of particular radar platforms. However, the effect of the operator may be included as one of the unspecified factors covered by the random variable RWC.

In summary, the radar detection model used in the SWIM game is overly simplistic and although it makes use of an accepted modeling technique, several of its basic assumptions cannot be supported. Additionally, it fails to take into account, or even discuss, a major radar limiting environmental factor. Stochastic processes are constrained by the physical environment and therefore if a major environmental effect is disregarded when developing a stochastic model, it is unlikely that the model will adequately represent reality. In as much as SWIM is an anti-submarine warfare game and acoustic devices are often considered the more important sensors, it is understandable that this game's radar detection model would be weak. However, since submarine launched cruise missiles are a significant threat to surface units, valid data concerning the outcome of simulated engagements between submarines and surface units can not be obtained if the radar detection model is unsatisfactory.

3.3. Warfare Analysis and Research System (WARS) Phase 2A. WARS is a prototype naval warfare gaming system currently in use at the U.S. Naval War College, Newport, Rhode Island. It provides the college

with a computer assisted war gaming capability to support both student and command gaming requirements. Student gaming is conducted in collaboration with the college's academic departments, while command gaming is conducted in response to the needs of major commands and activities external to the college.

Although designed around early 1960's computer technology, WARS has been developed incrementally into a versatile gaming system.[7] It is not a single game, but rather an adaptive system which, through the manipulation of input data, can simulate conflict environments from a one-on-one tactical situation involving individual units and weapons to a global strategic scenario involving opposing fleets of varied composition dispersed across thousands of square miles of ocean.

3.3.1. <u>WARS PHASE 2A Radar Detection Model</u>. The WARS radar detection model is contained in the system's detection module, DETECT, which provides detection information for all sensors during the play of a game.[8] It was developed in 1972 at the Fleet Combat Direction System Support Activity, San Diego, California.

Two different levels of the model are available to the WARS system, a basic model and a modified, or added realism model. Both forms use a logrithmic variation of the basic isotropic radar equation (see equation 2.12) to determine radar detection ranges as a function of radar capability, target reflectivity, and atmospheric absorption. The basic model goes no further than to determine the free space detection range of a radar and then comparing that range

to the calculated distance between the radar platform and a target. The added realism version modifies the detection range obtained in the basic model to include the effects of atmospheric refraction, radar horizon and radar lower look angle, and random delays in gaining contact.[9]

The basic element of accountability in both levels of the WARS DETECT module is the set. A set is defined as a grouping of one or more homogeneous platforms (ships, aircraft, submarines, etc.). The platforms comprising a given set are considered to be indistinguishable, each possessing characteristics and capabilities identical to all other platforms within that set. Therefore, in WARS the detection capabilities of the various radars are calculated against the characteristics of different target sets, (T_j), where j may assume values from 1 to m.

Using this concept of sets, the free space detection of a target set, say T_j, by some radar, say $(\text{Radar})_i$, is determined in both WARS detection models by solving the following equation for the radar detection range ρ:

$$(RDF)\rho + 2\log\rho = \log\left[\frac{(P_T)\ (G_T)}{4\pi}\right]^{1/2}_i + \log\left[\frac{G_A}{(N)\ (S_T)\ (4\pi)}\right]^{1/2}_i$$

$$+ \log\ (PCR)_i + \log\ (RCS)_j$$

$$+ 0.25\ \log\ (NP)_j \qquad (3.3)^{10}$$

where: P_T = average transmitted radar power
G_T = antenna gain
G_A = effective antenna area
N = average radar receiver noise
S_T = radar system threshold signal to noise ratio
$(RCS)_j$ = radar cross section of jth target set
$(NP)_j$ = number of platforms in the jth target set

In this equation those terms subscripted (i) and (j) represent the characteristics of radar $(Radar)_i$ and target set T_j respectively. Some of the terms in equation 3.3 are of particular interest. The Radar Damping Factor, (RDF), simulates atmospheric absorption of radar radiation and may be varied throughout a play of the game to represent, in part, changing environmental conditions. The Percent Capability Remaining, (PCR), is a term used to account for the dynamic deterioration of a radar's capability due to battle damage or other causes.[11] And finally, since the number of homogeneous platforms in a target set is directly related to the set's effective radar cross section, the range at which the set may be detected is directly proportioned to the number of platforms, $(NP)_j$, in the jth set. Therefore, the arbitrary term

$\log \left[(RCS)_j\, (NP)_j\right]^{1/4}$ or $\log (RCS)_j + 0.25 \log (NP)_j$ has been included in the WARS radar detection model to account for this relationship.[12]

Because the range at which a target may actually be detected is often significantly different from the range determined by equation 3.3, the added realism variation of the WARS radar detection model considers, as previously discussed, certain additional factors. The first factors considered are atmospheric refraction and radar horizon and lower look angles. The model assumes an index of refraction varying uniformly with altitude, which is summarized in the relationship

$$R_R = 0.75\ R_e = \text{Constant} \qquad (3.4)^{13}$$

where: R_e = earth's radius

This relation is substituted for R_e in the equation

$$d = -2\ R_e \tan\beta + (-R_e \tan\beta)^2 - 2\ R_e\ (h_R - h) \qquad (3.5)^{14}$$

which determines the range, d, at which a target at a specific altitude, h, will be within the radar's lower look angle and above the radar horizon. (see figure 3.1).[15] In equation 3.5,

where:
β = smallest angle of (ϵ, α)
ϵ = lowest angle at which the radar can point, lower look angle
$\alpha = -\sqrt{\dfrac{2h_R}{R_e}}$ radians, the angle of the radar horizon from a radar antennat at height h_R [16]

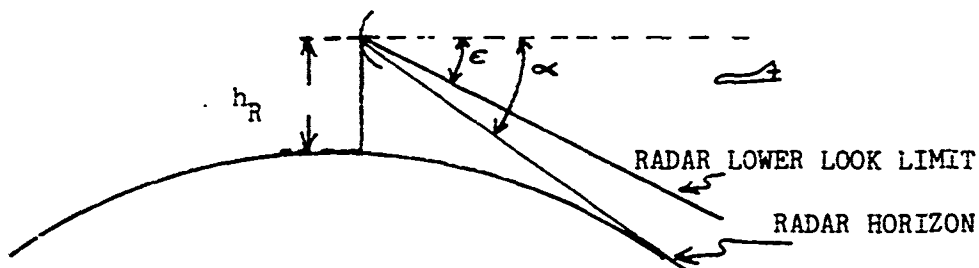

Figure 3.1. Illustration of Radar Lower Look Angle ϵ and Radar Horizon angle α.

Finally, in addition to the above modifying factors, the WARS enhanced radar detection model considers a stochastic variation in the time, and hence the range, at which a target is detected. This stochastic simulation is quite simple and is based on data contained in a study of the AN/SPS-30 Radar set.[17] Spefically, a random time delay, T_D, is computed from

$$T_D = \text{MIN}\ (k_D \times d,\ T_R) \times (RN) \qquad (3.6)^{18}$$

where: d = theoretical detection range
k_D = a constant for the radar
T_R = the time the target will be within sensor range based on game kinematics
(RN) = a random number uniformly distributed between zero and one

This time delay is then converted into a random variation in radar detection range based on the relative motion of the radar platform and target.

3.3.2. <u>Comment</u>. The WARS radar detection model has several excellent attributes. First, it permits the user to input actual radar and target parameters which allow the model to differentiate

between specific radar types. In particular the model enables the user to simulate long and short range air search and surface search radars. Second the model provides for dynamic changes in environmental factors and radar detection capability as a game progresses. Such changes occur in actuality and therefore, these variations add to the realism of the simulation. Finally, the model uses an interesting feature to increase the overall efficiency of the detection model. Prior to performing the relatively complex detection range prediction calculations, the model initially checks the distance between the radar platform and the target. If this distance exceeds the maximum possible detection range of the particular radar, and the target is not projected to pass within the maxmimum detection range of the radar during a specified time interval, then the prediction calculations will not be performed.[19] This of course requires that the user provide an actual, or arbitrary, maximum detection range for each different radar simulated by the WARS radar model.

Along with its good points the WARS radar detection model has some shortcomings. First, like the SWIM detection model discussed earlier, it uses the concept of sets to describe groupings of detector and target platforms. In WARS a set is by definition ". . . one or more homogeneous platforms, each indistinguishable from any other. Each platform in a set has precisely the same capabilities, and the sum of these capabilities determines the capability of the set."[20] This is a simplification of reality, particularly in the case of surface combatants, very few of which, if any, have exactly

identical capabilities. However, it may be argued that absolute differences which may exist among ships of a particular class are less significant than random variations in equipment operations. This may very well be the case, but if it is, then it should be so explained as a justification for using sets vice individual platforms. Since a WARS set may consist of one or more platforms, it would be possible to model ships (or aircraft and submarines) individually by designating single platform sets, each with unique capabilities.

A second shortcoming is that the model does not make use of all available radar parameter such as pulse width, pulse repetition rate, and frequency. Therefore, fine grain detection capability differentiation between individual radars is not possible.

A third shortcoming is that airborne targets are assumed to remain at a constant altitude. This is an unrealistic assumption, particularly if the airborne target is a cruise missile or an aircraft attacking a surface vessel with conventional ordnance. [illegible]straining an airborne target to a constant altitude may simplify radar range predictions during a specific time interval, but it reduces the realism of the simulation.

The WARS radar detection model addresses several major non-free space factors which affect radar propagation, specifically atmospheric absorption and simple refraction, the radar horizon and radar lower look angle. However, a fourth model discrepancy is that it does not either provide for or discuss radar interference patterns or fade zones resulting from the reflection of radar energy from the surface of the earth.

A final shortcoming is the model's failure to explicitly provide for the interaction of the radar operator and the influence of this interaction on the detection capability of particular radar platforms. However, the effect of the operator may be included implicitly in the time delay, T_D, which the model uses to randomly vary the detection range of different radars.

In summary the WARS radar detection model is a good basic model which provides the user with a great deal of flexibility in defining specific radar detection capabilities. It uses acceptable modeling techniques to simulate varying environmental and equipment conditions. Although it has several shortcomings, as discussed above, it does provide a basis for further development.

3.4. Naval Tactical Action Game (NAVTAG). NAVTAG exists in two forms, it is both a manual and a computerized naval tactical war game. The game was originally developed during the period 1969-1973 by LT Neil F. Byrne, USN, as a table top game. Since then, it has been used by numerous naval vessels on both the East and West coasts for basic tactical instruction and refresher training of shipboard tactical decision makers. The game, in its manual form, has recently been refined by the Surface Warfare Officer School Command, Department Head Course, Newport. Rhode Island and is being distributed to fleet units.

In 1978 the U.S. Naval Academy, Annapolis, Maryland, adopted NAVTAG to the school's computer system. The required programming

effort was accomplished by personnel of the Academy's Academic Computer Center for the Division of Professional Development. This computerized version of NAVTAG provides the students with an opportunity to demonstrate and develope their abilities to tactically employ various actual and hypothetical ship types in a multiple threat environment.[21] At the Naval Academy the game is an interactive simulation which permits participants to control platform kinematics, including altitude and depth, and the commission of weapons and sensors.[22]

3.4.1. NAVTAG Radar Detection Model. Although the computerized version of NAVTAG has been in operation at the U.S. Naval Academy for several months, a detailed functional description of the game's radar detection model has not yet been published. However, the general characteristics of the model were obtained through telephone conversations with persons at the Academy familiar with the game, and a review of the NAVTAG Participants Instruction Manual.

NAVTAG's radar model is essentially a stored data file. The radar detection capability of any individual platform against different targets is determined by radar range and detection probability data specified by the user for particular radar types and stored by the computer in a tabular file.[23] Radar detections are decided by simply comparing the distance between the radar platform and target to the stored radar detection ranges. In order for a detection to occur the target must be within range and above the

radar horizon. Given that the target meets these minimum conditions, detections are determined randomly based on the inputed probability of radar detection of a target at a specific range and altitude.

3.4.2. Comment. Due to the lack of published documentation it is difficult to comment in detail on the adequacy of the radar detection model used by the Naval Academy's version of NAVTAG, but some general observations can be made. First, it is basically a "cookie cutter" detection model, with only nominal provisions for the effects of environmental conditions and stochastic processes. It does not make use of individual radar parameters to compute detection ranges, although empirical detection data for particular radars may be used. And finally, except for the radar horizon, no environmental factors are considered.

Overall, NAVTAG's radar detection model appears to be unsophisticated, with limited flexibility. Its capability to simulate realistic radar phenomena, except in gross terms, is restricted by the requirement for the user to provide radar range data based on expected, or average, conditions.

3.5. Interactive Carrier-Exclusive Tactical Analysis Game (ICETAG).

ICETAG has been developed over the past two years by the Surface Warfare Development Group, Norfolk, Virginia. The primary purpose of the game is to analyze tactical concepts used by surface action groups (SAG's) in the absence of supporting carrier aircraft. Some

of the specific problems being examined with the aid of ICETAG are over-the-horizon targeting, surface-to-surface missile employment, and optimum mixes of combat systems and forces.[24] Additionally, although ICETAG's immediate application is tactical development and evaluation, it does have the potential to be utilized for tactical training, as demonstrated recently during a large scale iteration of the game at the Fleet Anti-Submarine Warfare Training Center, Atlantic.[25]

ICETAG, as a computerized naval tactical war game, has evolved around the WANG 2200 minicomputer. It uses two of these computers, one of which performs required sensor simulations. The necessary programming was done by personnel at the Naval Weapons Center, Dahlgren, Virginia under contract to the Surface Warfare Development Group.

3.5.1. <u>ICETAG Radar Detection Model</u>. ICETAG, like NAVTAG discussed in Sections 3.4 through 3.4.2, is an operational game, but a functional description of its radar detection model has neither been published nor written. However, a general description of the model was obtained during a telephone interview with the individual responsible for developing and programming the game's radar detection model at the Naval Weapons Center, Dahlgren.

The ICETAG radar detection model is based on a form of the free space radar equation (see equation 2.12). In the model, however, before this equation is applied a determination as to whether or not the target is visible to the radar is made by using the

standard radar horizon equation (see equation 2.15) and the known distance between the target and radar platform derived from the scenario geometry. If the target is above the radar horizon then detection is possible. The radar-to-target range is then used with the free space radar equation to calculate the signal-to-noise ratio of the reflected radar energy at the radar receiver. A probability of detection is then computed using this signal-to-noise ratio, the number of pulses per radar sweep impinging on the target, and the radar sweep, or scan, rate. Finally, a detection event is determined by a Monte Carlo technique using the calculated probability of detection.[26]

In playing the game users may simulate one to three separate and distinct radars on each surface platform. Normally these would include long-range air search, surface search, and fire control radars.[27]

3.5.2. Comment. As in the case of the Naval Academy's NAVTAG game, it is difficult to conduct a credible analysis of the ICETAG radar detection model without having the opportunity to examine written documentation. However, the interview with the model's designer, summarized in section 3.5.1, provided sufficient information to make several general and specific comments concerning the adequacy of the ICETAG radar detection model.

First, it is a very flexible model which makes use of the majority of available radar and target parameters. Specifically, in calculating the probability of detection it uses radar radiated

power, antenna gain, receiver sensitivity, beam width, pulse repetition rate, scan rate, and target radar cross section. By using these parameters the model is capable of fine grain simulation, resulting in unique characteristics for each individual radar in the game. This is realistic. Additional flexibility is provided by permitting the user to simulate up to three different radars on each surface platform, again this is a realistic attribute.

Not only is the ICETAG radar detection model flexible, but its probabilistic aspects are realistic in concept. In developing the model an effort was made to ensure that the physical characteristics of the radars and targets appropriately influenced the model's probability of detection calculations. Therefore as the various radar and target parameters are adjusted the probability of target detection varies accordingly.

On the negative side, except for the radar horizon calculations and normal atmospheric attenuation and spherical spreading, which is implicit in the free space radar equation, the model does not address all environmental factors. In particular the model does not make a provision for multi-path radar propagation and the resulting fade zones. The decision by the model's designer not to address all environmental factors detracts from the model's general utility. However, the designer felt that even without addressing such non-free space factors as radar interference patterns the model is still "ninety percent correct."[28] An additional consideration which led to the rejection of additional environmental factors from the model was the concern that their inclusion would reduce the

overall efficiency of the model by increasing required computer time.[29] Of course, if the model was to be run on a machine larger and faster than the WANG 2200, then this may not be a valid consideration.

In summary, the ICETAG radar detection model appears to be an excellent model with a great deal of flexibility and realism. Although it does not include provisions for radar fade zones and their subsequent modification of detection probabilities, this and other environmental factors could be included in the model at a later date. This model could form the basis of a very general and useful radar model, particularly if it were to be adapted to a more powerful computer.

3.6. Commander-in-Chief Pacific Fleet Warfare Environment Simulator (CPF WES). CPF WES is currently under development at the Naval Ocean Systems Center, San Diego, California as part of the Advanced Command Control Architectual Test bed project, with funding provided by the Defense Advanced Research Projects Agency. When finished, the CPF WES war gaming system will support a wide spectrum of CINCPACFLT requirements, which include:

"1. Pre and post-exercise analysis and evaluation.
2. Evaluation of the potential effectiveness of new weapon, sensor and communication systems.
3. Evaluation and comparison of tactical concepts.
4. Operation Plan development and evaluation."[30]

CPF WES will be an evolutionary product of the existing Warfare Environment Simulator (WES) gaming system presently operational at the Naval Ocean Systems Center (NOSC), San Diego.[31] Like WES, CPF WES will be an interactive system, but with significantly expanded capability. It will be able to simulate varying levels of tactical involvements from individual units and weapons to multiple unit formations of air, surface, and subsurface craft with their associated sensors, weapons, and communication systems.

As now envisioned, CPF WES will consist of four interconnected subsystems. Three of these will be "front-end" subsystems which will provide for player data input/output and display. The fourth subsystem will be the "core" which will perform data generation based on user inputs and stored data files. The hardware for the "front-end" subsystems will be located at NOSC, San Diego, the U.S. Naval Postgraduate School, Monterey, and CINCPACFLT headquarters, Hawaii. The "core" subsystem hardware will be colocated with one of the "front-end" subsystems at NOSC, San Diego. A system interface with the Fleet Numerical Weather Central (FNWC), Monterey will provide CPF WES with real time and predicted environmental data for the different scenario areas. The West Coast CPF WES facilities will be linked via satellite to the facility in Hawaii.[32]

The Initial Operational Capability (IOC) date for CPF WES is November 1979.

3.6 1. <u>CPF WES Radar Detection Model</u>. The radar detection model is one of a family of sensor models planned for CPF WES. These models

will operate either independently or jointly in order to simulate the total sensor environment. All sensor models, and therefore the radar detection model, are characterized by CPF WES documentation as being "fully parameterized," requiring the user to provide appropriate parametric data.[33]

Each of the sensor models has certain common features, two of which will be described briefly. First, in generating contact reports to the user, each sensor model will apply a location error to the reported target position. This error will be based on a user supplied Binormal distribution describing the characteristics of the sensor type. For controller information and post play analysis, the system will retain the true position of all targets generated.[34] Second, once a target detection event is allowed by a sensor model, contact with the target will be maintained by the system as long as target motion keeps it within the maximum detection range of the simulated sensor.[35] There are other features common to all CPF WES sensor models, but they are primarily concerned with overall system efficiency and will not be further addressed.

The CPF WES radar detection model itself is based on a logrithmic form of the standard radar equation, modified to account for the environmental factors of sea clutter and ducting.[36] This modified equation contains two general categories of terms, those representing factors which contribute to the strength of the reflected radar signal at the receiver, and those representing factors

which tend to degrade or obscure the reflected signal. The difference between these two groups of terms is defined as signal excess and equates to the strength, in decibels, of the target reflected signal received by the radar set.

The signal excess, SE, equation is

$$SE = P_T + 2_G + 2_W + TCS - 4DR - B - NF - L - C \qquad (3.7)^{37}$$

where: P_T = peak transmitted power, db/W
G = antenna gain, db
W = wavelength, db/cm
TCS = target cross section, db/m^2
D = ducting factor
R = target range, db/nm
B = receiver IF bandwidth, db/Hz
NF = receiver noise figure, db
L = radar system loss factor, db
C = sea clutter factor, db

As previously mentioned, this equation has been modified for CPF WES to include two environmental factors--sea clutter and ducting. Sea clutter is, in part, a function of significant wave height and results in radar signal losses and target obscuration due to scattering and excessive non-target signal returns. The value of the clutter factor, C, is determined by the relationship:

$$C = 10 \log (H_W) \qquad (3.8)^{38}$$

where: H_W = significant wave height, in feet

Ducting is an atmospheric phenomenon which causes electromagnetic radiation to be trapped between layers of the atmosphere, or between a layer of the atmosphere and the earth's surface. This may result

in both extended detection ranges and an apparent increase in the distance to the radar horizon because of reduced spreading losses (cylindrical vice spherical spreading) and increased electromagnetic refraction, causing the radar signal to closely follow the earth's surface. Although there are different causes of ducting, and ducting may occur at various altitudes, the CPF WES radar model covers only the case of the surface evaporation duct. This duct occurs as a result of the sharp relative humidity gradient in the vicinity of the air-sea interface. The value of the ducting factor, D, varies from 1.0 to 1.4 depending on the relative strength of the duct as decided by meteorological conditions. Ducting, in this model, is applied only to shipboard radars.[39]

As in the other radar detection models discussed in this paper, the target must be above the radar horizon in order for detection to be possible. When standard atmospheric refraction exists, the radar horizon is computed by

$$R_H = 1.25\,(\sqrt{H_R} + \sqrt{H_T}) \qquad (3.9)$$

where: H_R = radar antenna height, in feet
H_T = target altitude, in feet

If a surface evaporation duct exists, then R_H is extended in relation to the strength of the duct.[40]

In addition to calculating signal excess and determining whether or not the target is visible above the radar horizon, the CPF WES radar detection model computes the number of pulses N_p illuminating the target during each radar sweep using the relationship

$$N_p = PRR \left(\frac{BW}{SW}\right)\left(\frac{60}{ARR}\right) \qquad (3.10)^{41}$$

where: PRR = pulse repetition rate
BW = horizontal beam width, in degrees
SW = angular width of swept sector, in degrees
ARR = scan rate, in scans per minute (same as sweep rate)

Using SE and N_p as entering arguments, the model accesses a tabular file of detection probabilities. This probability table is based on a family of curves developed by L. V. Blake[42] relating probability of detection, P(det), to signal excess and N_p.[43] The table is derived for a specific false alarm rate and is used with all radars simulated by CPF WES. For illustrative purposes a portion of the P(det) table is reproduced below.

N_p \ SE(db) ------	-10	-8	-6	---------------	18
10	0	0	0	--------	.98
20	0	0	.02	--------	.98
30	0	.02	.04	-------	.99
⋮	⋮	⋮	⋮		⋮
80	.02	.03	.10	----------	.99

Figure 3.2. Partial Reproduction of CPF WES Radar Detection Probability Table.[44]

Radar detection of a target is determined by applying a random number test to the value of P(det) obtained from the probability table. In order to achieve a higher level of game efficiency this random number test is not applied for values of SE and N_p corresponding to P(det) $\geq$ 0.99 or P(det) $\leq$ 0.01. Without further computation detection is allowed if P(det) $\geq$ 0.99 and is disallowed if P(det) $\leq$ 0.01.

Finally, the CPF WES radar model has a provision for radar jamming. If jamming is present, a noise power level, as seen by the radar, is calculated and compared to NF (see equation 3.7). If the level of the jamming signal exceeds NF, then it is substituted for NF in equation 3.7 to obtain SE under jamming conditions.[45]

3.6.2. Comment. Overall the CPF WES radar model is excellent, with some particularly interesting and useful attributes. First, because it makes extensive use of player provided radar and target parameters, it is a very flexible model with the capability to simulate the majority of current and future pulse modulated radar systems. Further, the user has a choice of identifying surface radar platforms either by class, for example, Knox class frigate, or by individual unit, for example, USS PATTERSON (FF-1061). Consequently surface platforms may be assigned either general class or specific unit radar characteristics. Second, provisions have been made in the CPF WES radar model for the important environmental factors of sea clutter and ducting. The inclusion in the model of these two

factors enhances its realism, particularly with the system's capability to accept real world meteorological data from the FNWC. Third, the model uses interdependent physical and stochastic calculations to determine target detection and location. This adds to the model's realism by initially determining a detection event based on pulse integration and signal strength and then by reporting target location with an included position error.

There are several model deficiencies which have been recognized by the model's designers and which will be addressed in post IOC system enhancements. First, the sea clutter factor considers only wave height. There are other elements which affect sea clutter and the following, as a minimum, will be included in future model modifications: grazing angle, antenna height, and sea surface reflection coefficient. Second, the ducting factor considers only the surface evaporation duct. A post IOC CFF WES enhancement will model elevated refractive ducts resulting from anomalies in the atmospheric refraction index gradient.[46] And finally, the model's P(det) table is valide for only one false alarm rate. Subsequent model variants will provide several P(det) tables, each associated with a different false alarm rate. This will permit the user to select different P(det) confidence levels.

Even though the model designers have recognized several shortcomings and plan to correct them at a latter date, there are some additional deficiencies which were not discussed. First, the model does not have a specific provision for dynamic deterioration of sensor capability resulting from battle damage or other causes.

Second, the model does not explicitly simulate the radar set operator. However, the influence of the operator may already be covered in the system loss factor, L, or in the calculations used to construct the P(det) table. And third, although the model designers have taken different environmental factors into account, they have not looked at the multi-path propagation problem and resultant fade zones. Neglecting the radar interference pattern question introduces artificialities into the model. In particular, by not introducing fade zones into the model the designers were able to make the assumption that once a target is detected, contact is maintained with the target while it remains within maximum radar detection range. In actuality this is an invalid assumption. Contact with an air target can not in general be maintained by a surface mounted radar due to altitude and range dependent field strength variations in the radar radiation pattern.

In summary, the CPF WES radar detection model is excellent. It is both realistic and adaptable to various tactical situations. Although it has several deficiencies, most have been recognized and addressed by the system's designers. As it now exists the CPF WES radar model has significant potential for continued development and refinement.

3.7. Conclusion. This chapter has reviewed the radar detection models used by five computerized naval war games with tactical applications. Some models have common elements, but each is unique to a particular game, or gaming system. None of the models examined

had the capability to simulate radar fade zones. This is considered to be a serious shortcoming, since without this capability games users are presented with an unrealistic view of radar detection and tracking continuity.

Models do exist which could be used by computerized naval war games to simulate radar fade zones. One such model by L. V. Blake will be reviewed in chapter four.

NOTES

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32. Ibid., pp. 1-2 - 1-5.

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34. Ibid.

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36. Ibid., p. 5-36.

37. Ibid.

38. Ibid., p. 5-37.

39. Ibid., pp. 5-37 - 5-38.

40. Ibid., p. 5-37.

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42. See L. V. Blake, A Guide to Basic Pulse-Radar Maximum Range Calculations, Naval Research Laboratory Report 6930, 23 Dec 1969, Defense Documentation Center accession AD 701321.

43. CINCPACFLT Warfare Environment Simulator (CPF WES) System Functional Design Specification (Rough Draft), p. 5-39.

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CHAPTER 4

4.1. Introduction. The radar detection models of five separate computerized naval war games were critically examined in Chapter 3. Each model was unique and represented different levels of simulation sophistication. However, none of the models reviewed took into account radar radiation field modifications resulting from the phasor-vector addition of direct and reflected patch electromagnetic energy (see Section 2.7).

Although the war game models described in this paper do not consider radar radiation interference patterns, the mathematics defining the phenomenon are well known and have been incorporated into several computer driven, non-war game radar detection models. Two of these models were reviewed during the research for this paper. The first, Machine Plotting of Radio/Radar Vertical-Plane Coverage Diagrams, was written by Lamont V. Blake of the Radar Geophysics Branch, Radar Division, Naval Research Laboratory. And the second, Radar Simulation and Analysis by Digital Computer, was developed by D. M. White of the John Hopkins University Applied Physics Laboratory. Of the two models Blake's is the more limited in scope. It simply models radiation field variations in radar interference patterns. White's model on the other hand is a comprehensive simulation which attempts to analyze total radar performance in a dynamic environment.

While both of these models are excellent simulations, Blake's more closely resembles a functional software module. Because of this, and its restricted scope, Blake's model is conceptually easier to integrate into existing war game detection models than in White's. For these reasons this chapter will focus on a review of Blake's simulation and will suggest a possible interface between it and current computerized naval war game detection models.

4.2. <u>Machine Plotting of Radio/Radar Vertical-Plane Coverage Diagrams</u>. The Machine Plotting of Radio/Radar Vertical-Plane Coverage Diagrams model, hereafter referred to as the "Vertical-Plane Coverage" model, was developed in 1970 by Lamont V. Blake for the Radar Geophysics Branch, Radar Division, Naval Research Laboratory. Blake's purpose in formulating this model was to develop a procedure which could be used on modern digital computers to calculate and plot the vertical-plane radiation patterns of search radars, taking into account the interference of direct and earth reflected radar energy. Blake felt that by using these calculations and resultant diagrams a researcher could predict with accuracy regions in a radar's search pattern where targets would or would not be detected based on minimum required target reflected signal strength. This model was not intended to be used with war games, but rather to assist radar system designers and operations analysts.[1]

Blake's Vertical-Plane Coverage model is programmed in FORTRAN and consists of two major sets of subroutines. The first set calculates and plots maximum radar detection range contours on range-height-angle charts. The second set of subroutines calculates and plots signal level as a function of range given a target at a constant altitude.[2] Without repeating the details found in Blake's report on the Vertical-Plane Coverage model, the major features of both of these subroutine sets will be reviewed in the following two sections.

4.2.1. Radar Detection Range Contour Subroutines. This set of subroutines developed by Blake to plot maximum radar detection range, or constant signal level, contours is valid for " . . . antenna heights that are within a few hundred feet of the water and for targets that are at much higher altitudes and not too close to the horizon."[3] The geometry upon which this subroutine set is based is illustrated in figure 4.1. It should be noted that this geometry is not necessarily unique to Blake's maximum radar detection range contour subroutines, but describes in general the interference of direct and reflected path electromagnetic energy.

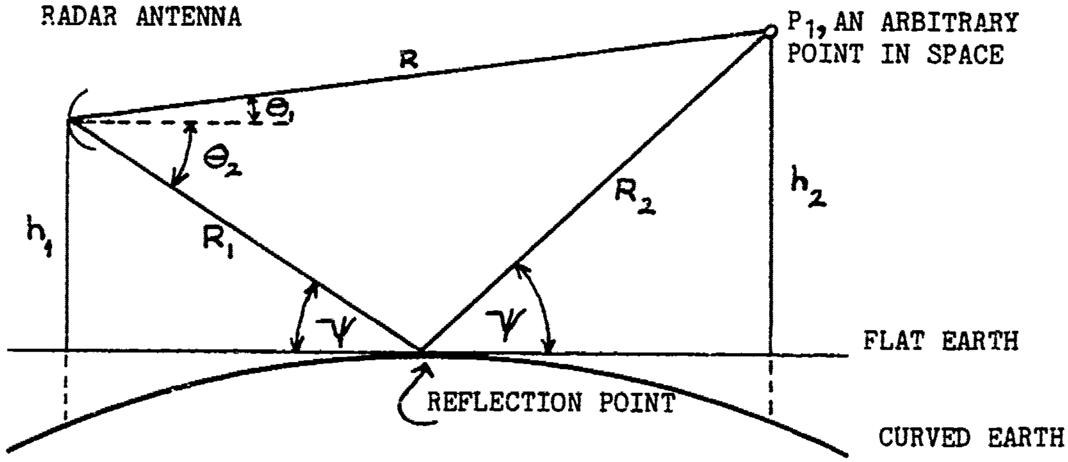

Figure 4.1. Geometry of the Surface Reflection Interference Problem[4]

Using the geometry in figure 4.1, and an adaptation of D. E. Kerr's mathematical analysis,[5] Blake developed his maximum radar detection range contour subroutines based on a term called the pattern propagation factor, F, defined as:

$$F = f(\theta_1) \left| 1 + x e^{-j\left(\frac{2\pi\delta}{\lambda} + \phi\right)} \right|$$
$$= f(\theta_1) \left| \sqrt{1 + x^2 + 2x\left(\cos\left(2\pi\delta/\lambda + \phi\right)\right)} \right| \qquad (4.1)^6$$

where: $f(\theta_1)$ = a function describing the antenna pattern of the direct path energy as it leaves the radar antenna

- λ = radar operating wave length
- x = general reflection coefficient
- ϕ = phase angle
- δ = difference between the direct and reflected paths, $(R_1 + R_2) - R$

Although not readily apparent from equation 4.1, F is the ratio of the actual electric field strength at a specific point in space, P, to that which would exist at the same point given no surface reflection.

In order to more closely simulate the environment of a seaborne air search radar, equation 4.1 was developed to include factors for earth curvature, surface roughness, and the phase shift experienced by electromagnetic energy reflected by sea water. These qualifying factors are contained in the terms δ and ρ .

In the case of δ , the difference between the direct and reflected paths, if the earth's surface was flat, then:

$$\delta \sim 2\, h_1\, h_2/d \qquad (4.2)^7$$

where: d = horizontal distance between the antenna and P
$d^2 \gg h_i^2$

There are many sets of circumstances in which equation 4.2 would be a valid approximation. However, since the earth is not flat, this expression is insufficiently general to be useful in all situations. Therefore, a correction factor was applied to 4.2 to account for earth curvature. This correction factor, J, is a function of the actual height above the earth of the radar antenna and P, standard atmospheric refraction, and the horizontal distance between the antenna and P. In his paper on the Vertical-Plane Coverage model, Blake describes the derivation of J. Without repeating the discussion

$$J = (1 - S_1^2)\ (1 - S_2^2) \qquad (4.3)^{8}$$

where: S_1 and S_2 are functions of the following (see Blake's raport for details): (a) the heights of the radar antenna and point P_1, (b) the horizontal distance between the antenna and P_2 (c) the earth's effective radius A_e[9]

When J is applied to equation 4.2

$$\delta = (2h_1\ h_2/d)\ (1-S_1^2)\ (1-S_2^2) \qquad (4.4)^{10}$$

In the case of x, the generalized reflection coefficient, correction factors for earth curvature, surface roughness, and sea water reflection have been incorporated. For Blake's model x is defined as

$$x = \frac{r\ D\rho_o\ \ f\ (\theta_2)}{f(\theta_1)} \qquad (4.5)^{11}$$

where: r = surface roughness factor
D = divergence, or curvature factor
ρ_o = the intrinsic reflection coefficient of sea water
$f\ (\theta_1)$ = a function describing the antenna pattern of the direct path energy as it leaves the antenna
$f\ (\theta_2)$ = a function describing the antenna pattern of the reflected path energy as it leaves the antenna

The surface roughness factor, r, is a function of wave height, radar wave length, and grazing angle and is defined as:

$$r = \exp\left[-2\left(\frac{2\pi H\ \sin\psi}{\lambda}\right)^2\right] \qquad (4.6)^{12}$$

where: H = average wave height
λ = radar wave length
ψ = grazing angle[13]

D, the divergence, or curved earth, factor for x in equation 4.5 is derived using the same parameters as for J. Again, without duplicating Blake's derivation, the divergence factor is:

$$D = \left[1 + \frac{4S_1^2 S_2^2 T}{S(1-S_1^2)\ (1 + T)}\right]^{-1/2} \qquad (4.7)^{14}$$

where: S, S_1, S_2, and T are functions of the actual height of the radar antenna and P, the horizontal distance between the antenna and P, and the earth's effective radius A_e (see note 9)

The value of ρ_o, the intrinsic reflection coefficient of salt water, depends on radar signal polarization, the grazing angle ψ, the radar wave length, and the complex dielectric constant of sea water. The calculations required to determine ρ_o cannot be reduced to a single, simple expression. Those desiring an explanation of these calculations are referred to Blake's Vertical-Plane Coverage model report. Also contained in this report are computer program listings used to compute ρ_o, along with the associated phase angle ϕ, for sea water reflection of radar energy.

As previously mentioned, Blake's set of radar detection range contour subroutines is based on equation 4.1 and its modifying factors discussed above. This equation defines the field strength of the ratio of a radar's interference and isotropic radiation patterns. This ratio, or pattern propagation factor, F, mirrors the

lobes of the alternating zones of signal maxima and minima described in Section 2.7 and in general

$$0 \leq F \leq 2$$

Vertical maximum detection range contours are computed by multiplying F by the radar maximum free space detection range and applying appropriate transformations to account for various elevation angles. The radar's maximum free space detection range is a required input for Blake's range contour subroutines, and may be either an assumed value or a value calculated by a separate subroutine such as found in some computerized war game radar models.

Besides the maximum free space detection range, other inputs required for Blake's detection range contour subroutines are: radar antenna height (feet), radar frequency (MHz), antenna beam width (degrees), sea wave height (crest to trough, feet), and signal polarization (vertical or horizontal). As with the radar's maximum free space detection range, the inputs could be provided by other computer programs such as might comprise a computerized war game master sensor detection model. Note that the target's altitude is not a required input. This is because the interference pattern phenomenon is a result of the physical environment in which a radar is operated and will be present regardless of the target's position.

The outputs of the calculations discussed in this section are plots of maximum non-free space radar detection range contours in a vertical plane on a range-height-angle coordinate grid as illustrated in figure 4.2.

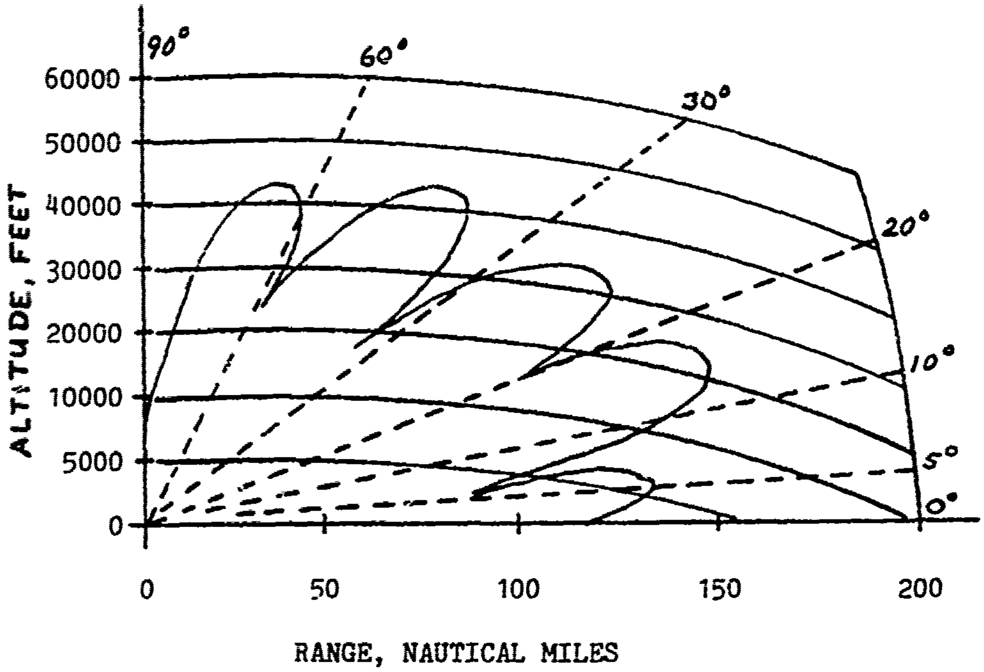

Figure 4.2. Example of Plot obtained from Blake's Radar Detection Range Contour Subroutines

These contour plots may also be interpreted as constant signal strength diagrams. That is, they graphically display the locus of all points in space where the strength of radar energy reflected from a target is equal to the radar's minimum detectable signal.

Although Blake's radar range detection, or constant signal strength, contour subroutines have broad application and can be extremely useful, the calculations involved are invalid for low radiation angles. To solve this problem, Blake incorporated into his Vertical-Plane Coverage model a second set of subroutines with which to describe low angle and low altitude radar radiation patterns.

4.2.2. Echo Signal Strength versus Range Subroutines. In general the total radiation field of a radar depicted in terms of three regions as shown in figure 4.3.

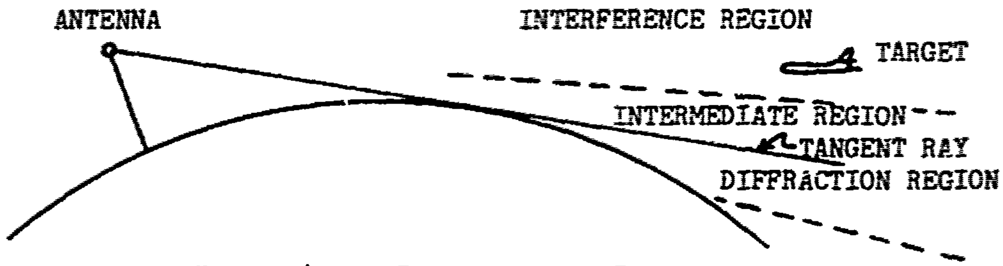

Figure 4.3. Interference, Intermediate and Diffraction Regions[15]

The first of these regions, well above the radar horizon, is the interference region where the radar radiation pattern is the result of interference between direct and reflected rays. The second region, located below the radar horizon, is a zone of weak radiation called the diffraction region, which as its name implies, results from electromagnetic diffraction. And finally, there is the intermediate region, a relatively narrow transition zone between the interference and diffraction regions.

Each of these regions requires different mathematical relations to define its associated radar pattern propagation factor, F, which in turn defines the radar's detection capability within the region. The method for calculating F discussed in Section 4.2.1 is valid only for the interference region, at elevation angles of greater than zero degrees. In the diffraction and intermediate regions the principles of ray optics upon which equation 4.1 is

based are not applicable. Therefore, in order to include the diffraction and intermediate regions in his Vertical-Plane Coverage model, Blake developed a second set of subroutines based on an alternate mathematical model.

Blake's second subroutine set, like his first, uses a mathematical foundation originally developed by D. E. Kerr (see note 5). However, instead of computing detection range, or constant signal strength, contours this set of subroutines calculates echo signal level, in decibels, as a function of range for a target at a fixed low altitude. The relation used to calculate these signal levels is

$$S_{db} = 40 \log_{10} (FR_0/R) \qquad (4.9)$$ [16]

where: R = specified radar to target range, nautical miles
R_0 = assumed maximum free space radar detection range. nautical miles
F = pattern propagation factor for range R

The specific calculations used to determine the value of F in equation 4.9 depend on the particular value of the direct, R, and reflected path, $R_1 + R_2$ distances. If the difference, S, between the direct and reflected path distances is such that

$$0 < \delta \leq \lambda/4$$

where: λ = radar wave length
δ = difference between direct and reflected paths [17]

then the target's position is assumed to be in the lower portion of the interference region near the intermediate region, and F is computed from

$$F = (1 + x^2 + 2x \cos \alpha)^{1/2} \qquad (4.10)^{18}$$

This equation is the same as 4.1 with

$$f(\theta_1) = 1$$

In the case where

$$\lambda/4 < \delta$$

the target is considered to be in the intermediate and diffraction regions and F is determined by an interpolation procedure and a group of empirical equations based on the relation:

$$F = V(x)\, U(Z_1)\, U(Z_2) \qquad (4.11)^{19}$$

where: X, Z_1, and Z_2 are functions of target range, antenna height, target height, and radar operating frequency (see Blake's report for details)

Using the results of calculations based on equations 4.9 through 4.11, the Vertical-Plane Coverage model constructs a plot of echo signal strength as a function of target range. The significant parameter inputs required by Blake's second subroutine set are antenna and target height (feet)--both fixed, radar frequency (MHz), sea wave height (crest to trough, feet), signal polarization (vertical or horizontal), and the calculated or assumed maximum free space range of the radar (nautical miles).[20]

Figure 4.4 is an illustrative example of the type of plot produced by Blake's echo signal strength versus range subroutines.

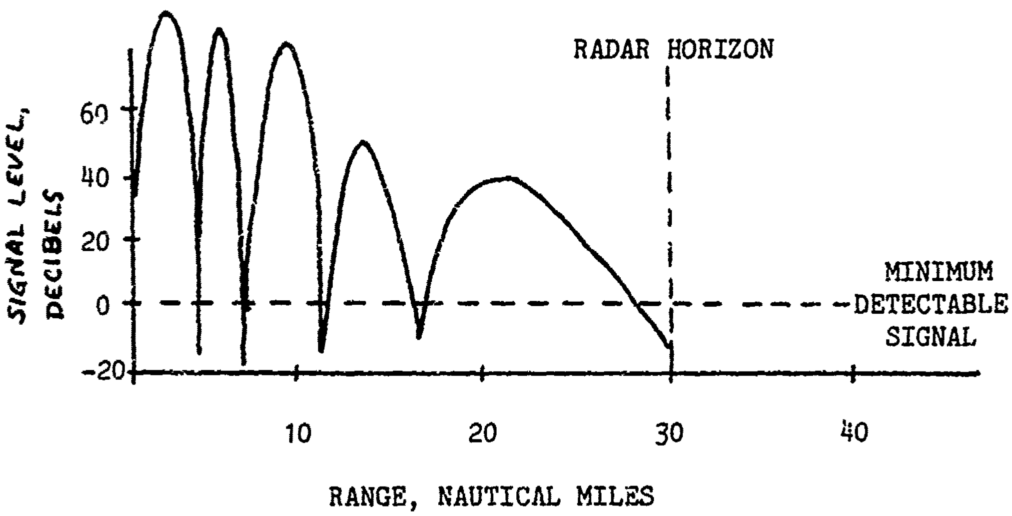

Figure 4.4. Example of Plot obtained from Blake's Echo Signal Strength versus Range, fixed Altitude Target, Subroutines

In this model, as shown in figure 4.4, the zero decibel level equates to the radar's minimum detectable signal. Therefore, those portions of the curve above the zero decibel level represent detection zones while those below that level represent areas of no detection, or fade zones.

4.3. Remarks. For the purposes of this paper Blake's Vertical-Plane Coverage model is excellent since it is potentially capable of correcting of the major deficiencies found in each of the five radar detection models examined in Chapter 3. This deficiency being of course their lack of capability to realistically simulate radar

radiation patterns. A possible interface between those models and Blake's will be discussed in Section 4.4. However, before proceeding with that discussion, a few comments should be made concerning several shortcomings found in the Vertical-Plane Coverage model.

First, Blake's model is strictly deterministic. Targets are either in a region where they can be detected or they are not. This may not be a particular problem if the model is used as a module of a master sensor detection program which would determine the probabilities of detecting a target in a fade zone, or not detecting it in a region of signal maximum. The next shortcoming is that the calculations used to derive radiation patterns at low elevation angles are dependent on target altitude or, more specifically, the echo signal strength versus range subroutine compute variations in a single horizontal section of the total radiation field. If the radiation pattern at a different altitude is required, then the plot must be recalculated. Given sufficient computer capability to accomplish these additional computations, or given a scenario in which the altitude of a low elevation angle target remains constant, then this becomes less of a concern. And finally, all radiation pattern calculations in the Vertical-Plane Coverage models depend on an assumed or computed value for a radar's maximum free space detection range. This value is not only a function of the radar's own unique characteristics, but also those of the target's--in particular the target's radar cross section. Therefore, each set of calculations

produced by the model is valid for only one radar and target combination. This problem could be partially solved by calculating maximum free space detection ranges for different radars using the expected value of target radar cross section. The use of radar cross section expected values would introduce a probabilistic aspect into the model which, as previously mentioned, could be addressed by a master detection program.

4.4. War Game Interface. Each of the computerized naval war games reviewed in this paper was provided with a different radar detection model. Although various environmental factors were considered by the models, none had the capability to simulate the effects of the earth's surface on radar radiation patterns. This deficiency is considered significant since it implies that all radar detections and subsequent events simulated in these games are based on the assumption of a continuous radar radiation field. However, such homogeneous radiation fields do not exist in the general case. Therefore, in order to correct this invalid implicit assumption, and increase the simulation quality of these games, their radar or general sensor detection programs should be modified to account for radar interference patterns.

Since the war game radar detection models described in Chapter 3 either already exist, or are in an advanced state of development, it is more desirable to augment them with an interference pattern capability than to rewrite them in their entirety to account for this phenomenon. This augmentation should take the form

of an auxilliary software package, or module, which could be called by a master detection routine whenever radar signal maxima and minima lobe calculations are required. In order to conserve programming effort, an existing computerized radiation pattern model should be utilized as the basic augmentation package. Blake's Vertical-Plane Coverage model is an example of a currently available model which could be used for the radiation pattern augmentation of existing or planned computerized naval war game detection models. The following is one way in which Blake's model could be integrated into computerized war games.

The general concept of this integration is to use the Vertical-Plane Coverage model as a subroutine within the selected war game's overall detection model to establish a target's position relative to a radar's radiation pattern of signal maxima and minima. That is, given a scenario, along with specific radar and target parameters, Blake's model would be used to determine if an airborne target's position, relative to a particular radar, was such that its nominal reflected signal could be detected by the radar's receiver. If the Vertical-Plane Coverage model places a target's position in a region where its nominal reflected signal strength would be above the radar's detection threshold, then the game's master detection routine would be required to decide the outcome of the detection event. Depending on the game, target detection could be allowed without further calculation, or a probability procedure might be applied to decide whether or not detection occurred. Similarly, if the Vertical-Plane Coverage model determined that a

target was in an area where the nominal strength of its reflected signal was below the radar's minimum detectable signal level, then the game's master detection model would again be required to resolve the detection event. In some games detection could be disallowed without further action. But, recognizing that due to spurious conditions targets are occasionally detected in radar fade zones, other games might employ a suitable probability routine to decide whether or not to disallow the detection.

Contingent on the specific war game involved, various modifications to Blake's model may be required in order to interface it with the game's detection model. At the very least it would be necessary to eliminate Blake's plotting routines and reformat his model's output. It is envisioned that the reformatted outputs would take the form of internally stored "radiation pattern matrices" derived from the individual outputs of the two sets of subroutines contained in Blake's model and described in Section 4.2.

Ideally a separate and distinct radiation pattern matrix should be constructed for each possible combination of radar and target class simulated in the game. However, from a practical point of view this could involve excessive resources in terms of computer time and capacity. If computer resource economy is required, the number of radiation pattern matrices could be reduced in two ways. First, using expected values for target parameters, specifically radar cross section, matrices would be calculated for each radar assuming an "average target." With this approach, the number of radiation pattern matrices required would be reduced to the number

of different radar types simulated. If more economy is required, then the second approach could be used. This would consist of calculating a single matrix using expected values for both target and radar parameters. Regardless of the number of matrices calculated, each would be developed in the same manner.

Since Blake's model uses two distinct sets of calculations to determine high and low altitude radiation patterns, the first step in computing the radiation pattern matrix is to define high and low altitude. For illustrative purposes, altitudes between 0 and 3000 feet will be considered low, while those over 3000 feet will be considered high.

Once the differentiation between low and high altitudes is made, the next step is to use Blake's two subroutine sets to provide the data for the radiation pattern matrix. This is done in two stages. First, the low altitude portion of the matrix is calculated, then the high altitude portion is computed and combined with the low altitude portion into one matrix.

The low altitude portion of the radiation pattern matrix is developed by a series of iterations of Blake's echo signal strength versus range subroutines. As previously discussed, the calculations in this subroutine are valid only for a single target altitude. Since it is not realistic to assume that a target would remain at a constant altitude, the echo signal strength versus range calculation would be repeated several times to establish the coordinates for a

family of curves representing various target altitudes between 0 and 3000 feet. For example, it might be decided to calculate echo signal strength versus range curves for 50, 100, 200, 300, 400, . . ., 2600, 2700, 2800, and 3000 feet.

Once the data points are computed for this family of curves and appropriate radar to target range increments selected, the data points are transformed into the low altitude portion of the radiation pattern matrix as follows. If at radar to target range R_i and altitude A_j, the value of the echo signal level S_k exceeds zero decibels, then a target's reflected signal at that point would be greater than the radar's minimum detectable signal level. The radiation pattern matrix element, $RPM_{i,j}$, corresponding to (R_i, A_j) would be assigned a value of 1. On the other hand if the echo signal level at (R_i, A_j) was less than or equal to zero decibels, then a target's reflected signal at that point would be insufficient for detection. The corresponding matrix element woud then be assigned a value of 0. Figure 4.5 is an example of how the low altitude portion of the radiation pattern matrix might appear.

A_j \ R_i	10	20	30	- - - - - -	200
50	1	1	1	- - - - - -	1
100	1	1	0	- - - - - -	1
200	1	0	0	- - - - - -	0
⋮	⋮	⋮	⋮		⋮
3000	1	0	0	- - - - - -	1

Figure 4.5. Example of the Low Altitude portion of the Radiation Pattern Matrix

The high altitude portion of the radiation pattern matrix would be developed in a manner similar to the low altitude segment, but using Blake's detection range contour subroutines. Since this set of subroutines is altitude independent it need be run only one time for each different radiation pattern matrix desired. After performing the calculations required for the construction of a detection range plot, a set of possible target positions, (R_i, A_j), would be selected and compared to the calculated detection contour. The radar to target range values, R_i, would be the same as in the low altitude case. However, the altitude values, A_j, of the selected high altitude target positions would start at some value greater than 3000 feet and increase at specified intervals to some predetermined maximum figure. If, in the high altitude

case, range R_i at altitude A_j was equal to or exceeded the detection contour's value of range at that altitude, then the point (R_i, A_j) would lie outside of the detection contour envelope. In this situation $RPM_{i,j}$ would be assigned a value of 0 indicating that the nominal reflected signal from a target at (R_i, A_j) would be insufficient for radar detection. Conversely, if range R_i at altitude A_j was less than the detection contour's value of range at that altitude, then point (R_i, A_j) would be inside the detection contour envelope. In this case $RPM_{i,j}$ would be assigned a value of 1 showing that the nominal reflected signal strength of a target at (R_i, A_j) exceeded the radar's detection threshold.

The values of the radiation pattern matrix elements determined using the detection contour subroutines would simply be added to those already established with the echo signal strength versus range subroutines in the low altitude case. The resultant matrix, illustrated in figure 4.6 would be stored for use by the war game's master detection routine.

	$A_j \diagdown R_i$	10	20	30	— — —	200
LOW ALTITUDE ELEMENTS	50	1	1	1	— — —	1
	100	1	1	0	— — —	1
	200	1	0	0	— — —	0
	⋮	⋮	⋮	⋮		⋮
	3000	1	0	0	— — —	0
HIGH ALTITUDE ELEMENTS	3100	1	1	0	— — —	0
	3200	1	1	1	— — —	0
	⋮	⋮	⋮	⋮		⋮
	60000	0	0	0	— — —	0

Figure 4.6. Example of a partial
Radiation Pattern Matrix

When interfaced with a computerized naval war game, the radiation pattern matrix would be entered using values of target altitude and range as determined by the game's kinematics. Should the game's target position not correspond to exact values of range and altitude used to compute the matrix, then the matrix would be entered using values of R_i and A_j closest to the target's simulated position. The value of $RPM_{i,j}$ extracted from the matrix would be used by the game as an input to its detection routines (the master detection model). Depending on the sophistication of the game's detection model, detection could be allowed or disallowed

simply on the value of $RPM_{i,j}$. But more preferably, a probability routine, appropriate to the position of the target relative to zones of signal maxima and minima, would be used to decide the outcome of the detection event.

Figure 4.7 diagrams the logic flow of this paper's suggested interface between Blake's Vertical-Plane Coverage model and a hypothetical war game detection model. It is recognized that other integration schemes are possible. For example, in some cases it might be possible to use the outputs of Blake's two subroutine sets directly without going through the intermediate step of constructing a binary matrix.

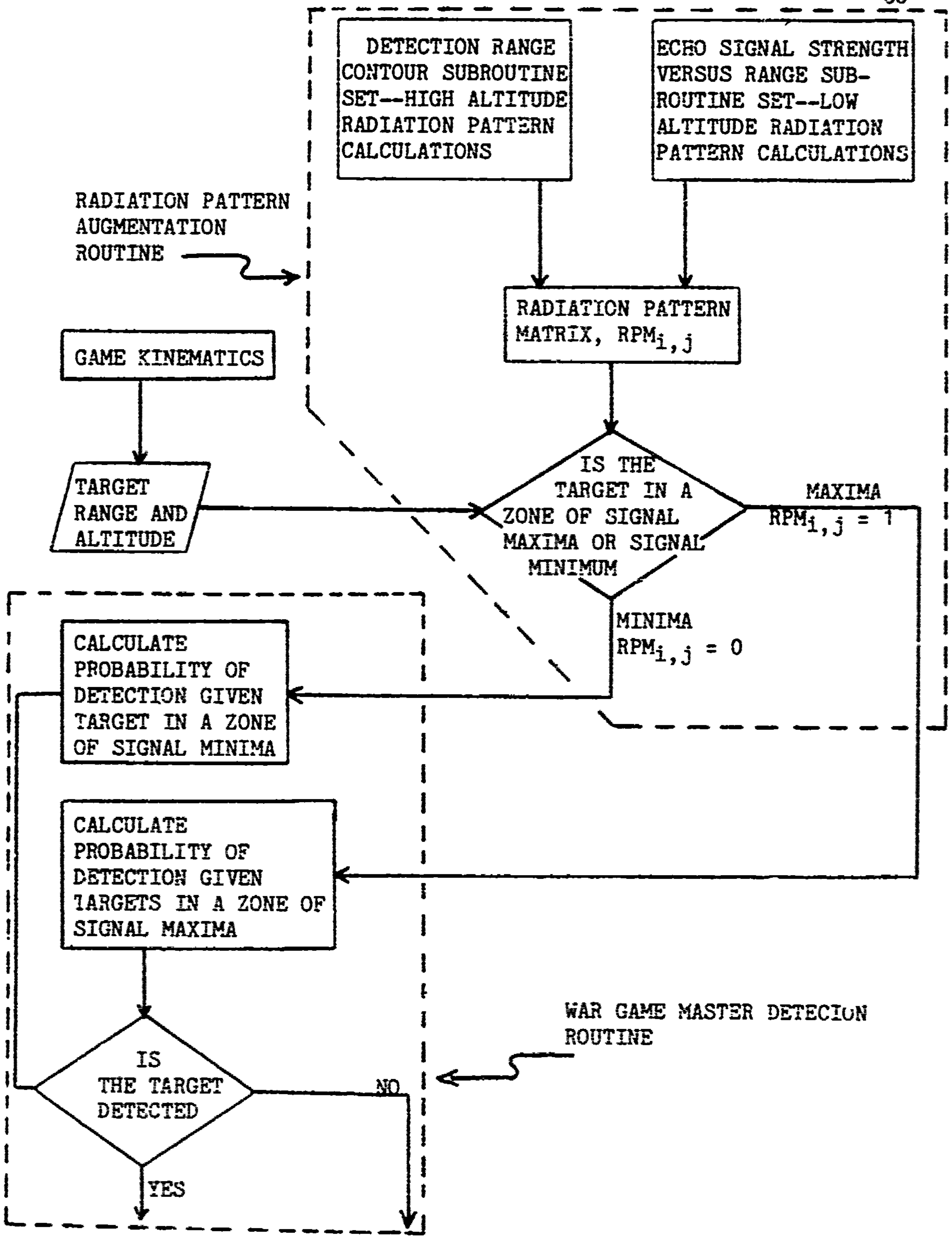

Figure 4.7. War Game Radiation Pattern Augmentation Logic Flow

4.5. Conclusion. This chapter has reviewed an existing computerized radar radiation pattern model which, with some modification, would be interfaced with any of the five war game radar detection models discussed in Chapter 3. It is realized that the integration of independently developed computer software is not necessarily a simple task. The programs may be in different languages, requiring that one or more be translated to a common language. Even given a common language, if the programs were written for use on different computers they could contain certain hardware specific characteristics which would need to be changed in order to use them on other pieces of equipment. Additionally, there may be numerous requirements to redefine variables and modify input and output formats. However, despite the various problems associated with interfacing different computer programs, it is easier to modify existing programs for new applications than to develop completely new programs for the same purposes.

NOTES

1. U.S., Department of the Navy, Radar Geophysics Branch, Radar Division, Naval Research Laboratory, Machine Plotting of Radio/ Radar Vertical-Plane Coverage Diagrams, by Lamont V. Blake (Washington, D.C.: Naval Research Laboratory, 1970), p. 1.

2. Ibid.

3. Ibid.

4. Ibid., p. 2.

5. Blake's source as identified in his report bibliography was Propagation of Short Radio Waves, MIT Radiation Laboratory Series Vol 13, ed. D. E. Kerr (New York: McGraw-Hill, 1951).

6. Lamont V. Blake, Machine Plotting of Radio/Radar Vertical-Plane Coverage Diagrams, p. 3.

7. Ibid.

8. Ibid., p. 4.

9. A_e is the earth's effective radius assuming standard atmospheric refraction. $A_e = (4/3)$ (Actual earth's radius).

10. Lamont V. Blake, Machine Plotting of Radio/Radar Vertical-Plane Coverage Diagrams, p. 4.

11. Ibid., p. 3.

12. Ibid., p. 5.

13. The grazing angle, is illustrated in figure 4.1. It can be derived from the expression $\tan \psi = \left(\frac{h_1 + h_2}{d}\right) K (S, T)$,

    see Lamont V. Blake, Machine Plotting of Radio/Radar Vertical-Plane Coverage Diagrams, p. 5.

14. Lamont V. Blake, Machine Plotting of Radio/Radar Vertical-Plane Coverage Diagrams, p. 4.

15. Ibid., p. 9.

16. Ibid., p. 21.

17. $\delta = \frac{2h_1 h_2}{d}$ or $\delta = R_1 + R_2 - R$, see Lamont V. Blake, Machine Plotting of Radio/Radar Vertical-Plane Coverage Diagrams, pp. 1, 10, and 22.

18. Lamont V. Blake, Machine Plotting of Radio/Radar Vertical-Plane Coverage Diagrams, p. 44.

19. Ibid., p. 10.

20. Ibid., p. 21.

CHAPTER 5

5.1. Summary. The purpose of this paper was threefold. First, to introduce basic pulse modulated radar theory while concurrently identifying those analytically descriptive parameters and environmental factors which should be considered in realistic radar detection models. Second, to evaluate the adequacy of the radar detection models found in current and planned computerized naval war games with tactical applications. And finally, if satisfactory radar detection models did not exist in those current or proposed games examined, then to suggest a suitable model. Each of these individual goals was achieved and, in addition, the research conducted revealed a requirement for the effective centralized management of computer supported war game development and employment in the U.S. Navy. A synopsis of the research required for this paper follows.

Background information on radar theory was obtained with little difficulty. Initial research was conducted at the Combined Arms Research Library, Fort Leavenworth, Kansas. However the publications immediately available at this facility were inadequate. Fortunately the library had direct access, through a computer terminal, to the resources of the Defense Documentation Center (DDC), Alexandria, Virginia. The DDC was a prolific source of documents covering all aspects of radar theory. Once specfic documents were identified they were ordered and received within two weeks. Over twenty documents on radar theory were thus obtained from the DDC. Of these, four were selected as primary sources for this

paper. The only non-DDC source used in the radar theory research was an American Radio Relay League publication from the author's personal library. The summary of pulse modulated radar theory and detection model parameters is presented in Chapter 2.

The research required to evaluate the adequacy of radar detection models used in computerized naval war games was not as straight forward as that required for the radar theory summary. The first problem encountered was simply identifying computerized naval war games either currently available or under development. A search of DDC files resulted in the idenfication of only one computerized naval war game with tactical application, the Sea Warfare Integrated Model (SWIM). Four other computerized war games were identified through a series of telephone conversations with personnel at the U.S. Naval Academy, the U.S. Naval War College, the Surface Warfare Officers School Command, the Surface Warfare Development Group, and the Naval Ocean Systems Center. All individuals interviewed were cooperative and provided as much information as possible on the war games with which they were working. However, none of these could provide information on the total war gaming effort in the U.S. Navy, and none was aware of any central control authority for naval war gaming.

Once the five war games reviewed for this paper were finally identified, a second problem was encountered--lack of documentation for two of the five games. This problem was overcome in part through telephone conversations with personnel responsible for these two games. After identifying the five war games and receiving, in

one form or another, available documentation the games' radar detection models were critically examined. Although each had certain merits none had a capability to simulate radar radiation patterns. This was considered unsatisfactory. Chapter 3 contains the results of this research and analysis.

Since none of the five war game detection models reviewed was considered satisfactory from the view point of adequately simulating radar radiation patterns, a model to provide this simulation capability had to either be found or developed. Because of the extensive radar research conducted by various government agencies and private concerns, it seemed reasonable that computer models which simulated radar radiation patterns already existed and therefore a new model need not be developed. The only problem then was to locate one of these models. This turned out to be a relatively easy task. While discussing the Interactive Carrier-Exclusive Tactical Analysis Game (ICETAG), an analyst at the Naval Weapons Center, Dahlgren, Virginia provided information concerning a radar radiation pattern model particularly suited for naval applications. This was the Vertical-Plane Coverage model developed at the Naval Research Laboratory by Lamont V. Blake. A copy of Blake's report describing his model was obtained from the DDC. This report then formed the basis of the radar detection model augmentation scheme suggested in Chapter 4.

5.2. Recommendations. The recommendations arising from the research conducted for this paper fall into two distinct categories. First are those relating to future research and second, those concerning administrative procedures for managing the computer war gaming effort within the U.S. Navy.

5.2.1. Future Research. Follow on research to this paper should focus on efforts to incorporate radar radiation pattern simulations into the radar detection models of computerized naval tactical war games. Wherever possible existing computer routines should be used. As discussed in Chapter 4 such software is in fact available.

Although it is entirely feasible to update existing war game detection models, in the interest of economy of effort it is recommended that this be deferred in favor of ensuring that war games currently in development are provided with a satisfactory radar detection model. An excellent candidate for this effort is the Commander-in-Chief Pacific Fleet Warfare Environment Simulator (CPF WES) game. It is recommended that Blake's Vertical-Plane Coverage model be interfaced with CPF WES in a manner similar to that suggested in Chapter 4.

5.2.2. Administrative Procedures. The recommendations presented in Section 5.2.1 follow naturally from the structure of this paper and the single major deficiency found in each of the five radar detection models examined. However, in the course of the research for this paper, a deficiency more significant than the shortcomings of

the various war game radar detection models was perceived. This is the apparent lack of effective centralized management of the Navy's computer war gaming effort.

Several organizations within the Navy have been, or are, actively involved in developing and using computer assisted war games for various purposes. During the research phase of this paper, personnel from five of these organizations were interviewed. The interviews indicated a general lack of knowledge on the part of these individuals concerning the overall status of computerized war gaming in the Navy. For the most part they were only vaguely aware of the war gaming activities in groups other than their own. Additionally, there was a tendency on the part of some of those interviewed to perceive their efforts as unique, with specialized application, either for training or for the evaluation of tactical concepts. These partisan views have apparently been sufficiently justified to permit the independent development of particular games. This parochialism restricts information interchange and results in duplication and fragmentation of effort and failure to incorporate into new games ideas and concepts previously developed.

In order to correct this situation it first must be recognized that well conceived computerized war games, with realistic simulation routines, have multiple applications. They are not necessarily either training devices or analytical tools, but can in fact be both. Acceptance of this view removes war games from partisan considerations and supports the requirement for centralized

management of computerized war game development. Therefore it is recommended that a central managerial and fiscal authority be established for computerized tactical war game development.

This central authority should ensure that new games are not developed without attempting to utilize previously developed games and software. It should provide a catalog of all existing computerized tactical war games and applicable computer routines. It should also ensure that documentation is developed concurrently with any new tactical war game. And finally it should strongly encourage commonality of game supporting computer languages and hardware.

As a closing comment, such a central authority as suggested in this paper may already exist. However, if it does, then its existence is unknown at the worker level in several organizations involved with computer supported war games.

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